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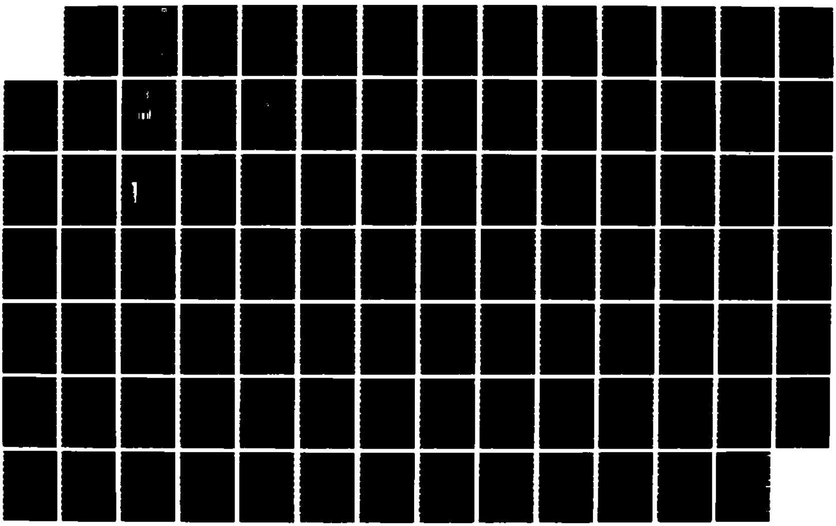

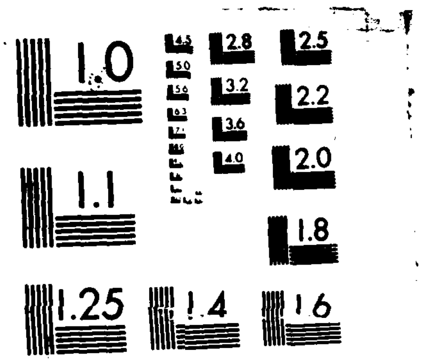

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Special Report 87-1

January 1987

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A freeze-thaw test to determine the frost susceptibility of soils

Edwin J. Chamberlain

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS
FEDERAL AVIATION ADMINISTRATION
FEDERAL HIGHWAY ADMINISTRATION

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

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A new freezing test for determining the frost susceptibility of soils is presented to supplant the standard CRREL freezing test currently specified by the Corps of Engineers. This test reduces the time required to determine the frost susceptibility of a soil in half. It also allows for the determination of both the frost heave and thaw weakening susceptibilities and considers the effects of freeze-thaw cycling. The new freezing test eliminates much of the variability in test results caused by the human element by completely automating the temperature control and data observations.

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PREFACE

This report was prepared by Edwin J. Chamberlain, Jr., Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Federal Highway Administration and the Federal Aviation Administration under Order No. FHWA 8-3-0187, Full-Scale Tests to Evaluate Frost Action Predictive Techniques, and by DA Project 4A762730AT42, Design, Construction and Operations Technology for Cold Regions; Task A2, Soils and Foundations Technology in Cold Regions; Work Unit 002, Seasonal Changes in Strength and Stiffness of Soils and Base Courses; and Task A3, Facilities Technology for Cold Regions; Work Unit 006, Volume Change Induced by Freezing and Thawing of Pavement Systems.

Members of the Board of Consultants reviewing this study are Dr. B.J. Dempsey, University of Illinois; Dr. D.G. Fredlund, University of Saskatchewan; Dr. M.E. Harr, Purdue University; E. Penner, National Research Council of Canada; and Dr. M.W. Witczak, University of Maryland. Special recognition is due R. Roberts for his assistance with the test program. The author also thanks H. Tomita and D. Carbee for reviewing the report.

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A FREEZE-THAW TEST TO DETERMINE THE FROST SUSCEPTIBILITY OF SOILS

Edwin J. Chamberlain

1. INTRODUCTION

Laboratory freezing tests are necessary to accurately characterize the frost susceptibility of soils. This is especially true for borderline granular materials used for the base and subbase layers in roads and runways.

The Corps of Engineers has employed a freezing test (Chamberlain and Carbee 1981) for more than 30 years. While this freezing test has proven adequate to identify and classify frost-susceptible soils, it suffers from several serious defects. Most significant of these are poor temperature control, indeterminate side friction, lengthy test period, lack of thaw weakening index, and provision for only a single freeze. Furthermore, correlation of the laboratory results with field performance is undocumented and the test appears to be overly conservative.

In a review of frost susceptibility index testing (Chamberlain 1981), the author concluded that no other available freezing test fulfilled current requirements for performance, efficiency and reliability. A new freezing test was needed, one that would address the deficiencies and draw upon current advances in test automation technology.

This report discusses the current Corps of Engineers practice for conducting freezing tests on soils, describes a new freezing test designed to replace it, outlines in detail test equipment and procedures, and suggests a method of classifying the frost susceptibility of soils based on both frost heave and thaw weakening. A companion report (Chamberlain 1986) discusses the selection process for this new freezing test in greater detail. Details on the automation of the test have also been reported elsewhere (Chamberlain 1984).

2. CURRENT FREEZING TEST PRACTICE IN THE CORPS OF ENGINEERS

The frost heave test employed by the Corps of Engineers was developed for evaluating the relative frost susceptibility of soils and granular base materials. It is often referred to as the CRREL freezing test. In this report it will be called the CRREL standard freezing test in deference to its long-standing use. Details of the test were first published by Haley and Kaplar (1952) and a comprehensive summary of test procedures and results was given later by Kaplar (1974). More recently, Chamberlain and Carbee (1981) described the current state of this freezing test.

In the standard test, materials are subjected to a very severe combination of freezing, moisture, and surcharge conditions that are conducive to frost heaving. The results do not quantitatively predict the actual magnitude of frost heave under field conditions, but they are designed to provide a relative indication of the potential for frost heave.

Soil samples are generally compacted to densities equivalent to AASHO T 180-57, saturated, and frozen from the top down at a constant rate of frost penetration of approximately 1.3 cm/day for 12 days. The samples are frozen in tapered, cast acrlytic cylinders that are Teflon-lined and lightly coated with silicone grease (Fig. 1) to reduce side friction. A porous stone at the base and a constant-head water supply are used to pro-

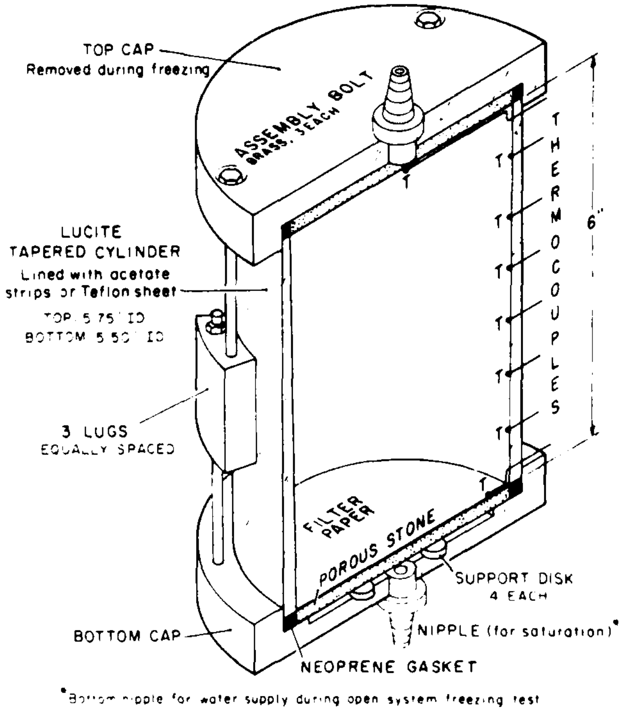

Figure 1. Inside-tapered freezing cell for confining the test sample in the CRREL standard freezing test (from Kaplar 1974).

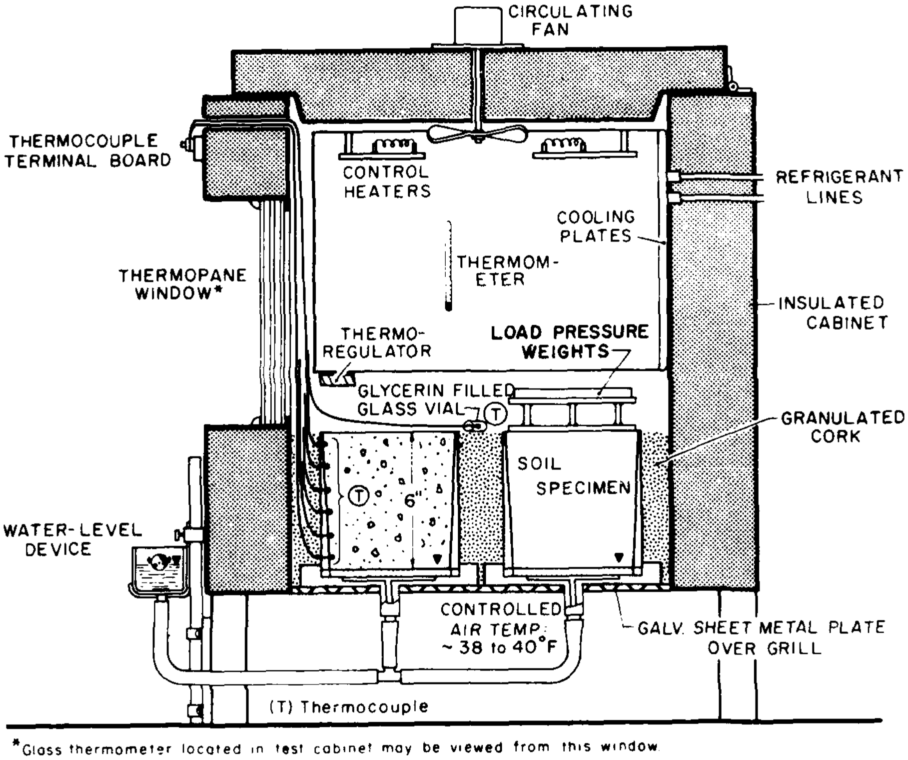

Figure 2. Cutaway view of the freezing cabinet for the CRREL standard freezing test (from Kaplar 1974).

vide a source of water 1 cm above the sample bottom. A surcharge of 3.5 kPa is placed on the sample to simulate 15 cm of asphalt concrete pavement. The samples are frozen in groups of four in a freezing cabinet (Fig. 2). The lower boundary air temperature is maintained at 4°C throughout the test while the upper boundary air temperature is lowered daily in steps to facilitate an average frost penetration rate of 1.3 cm/day.

The temperatures in the soil samples are measured by thermocouples placed through the cell walls and are automatically recorded by a data acquisition system. Frost heave is observed with linear motion potentiometers and continuously recorded, along with the thermocouple outputs, on the data acquisition system.

Frost depths are manually determined by plotting the temperature profiles and interpolating the position of the 0°C isotherm. The frost heave rate is determined from a plot of the heave versus time as the maximum rate occurring during the test period. Figure 3 shows typical results.

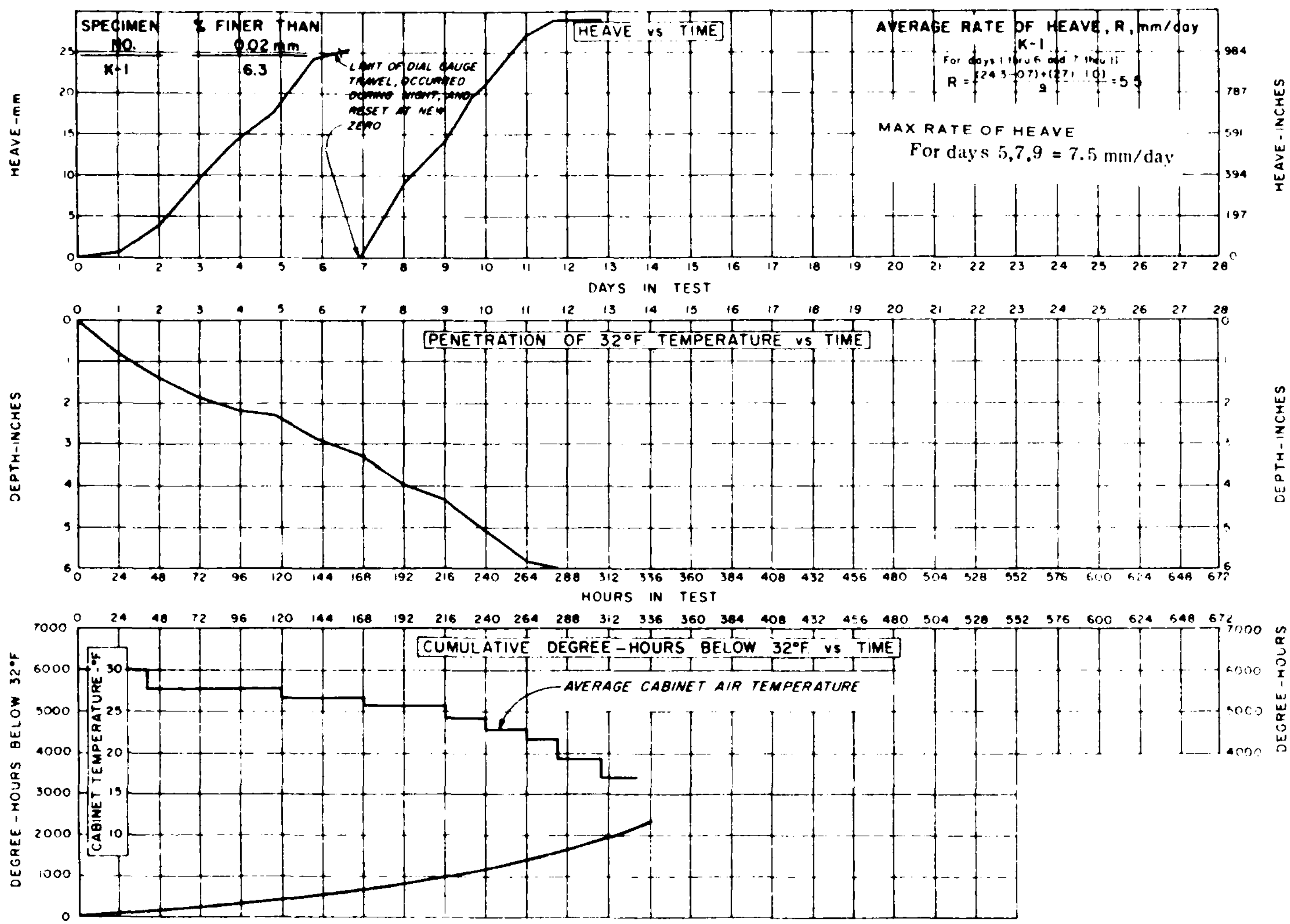

Figure 3. Typical results from the CRREL standard freezing test (from Kaplar, 1974).

Table 1. Frost susceptibility classification according to the standard CRREL freezing test.

Frost susceptibility	Average rate of heave (mm/day)
Negligible	0-0.5
Very low	0.5-1.0
Low	1.0-2.0
Medium	2.0-4.0
High	4.0-8.0
Very high	> 8.0

The frost susceptibility classification is obtained from Table 1 using the maximum heave rate determined from the freezing test.

3. LIMITATIONS OF THE STANDARD FREEZING TEST

The standard CRREL frost heave test has several limitations. The test is long (12 days) and is encumbered by the frequent temperature adjustments necessary to maintain the constant frost-penetration rate. And if samples of different thermal properties are tested together, the rate of frost penetration cannot be kept equal in each. There is also a problem with side friction, particularly with coarser grained materials. The test does not consider the effects of freeze-thaw cycling. Also, the test is principally an index test for frost heave and does not directly address thaw weakening, which is frequently more of a problem than frost heave. Finally, the test is very conservative and probably rejects many materials that would prove to be non-frost-susceptible under field conditions.

Most of these problems have been recognized for a number of years. As a result, a recent report (Chamberlain 1981) recommended that a new test be developed to address these problems. The report suggested that a new method be developed to eliminate side friction (possibly by using stacked rings), that constant temperature boundary conditions be employed with at least two freeze-thaw cycles, and that a California Bearing Ratio (CBR) test be conducted after the last thaw to determine thaw weakening characteristics.

4. DEVELOPMENT OF A NEW FREEZING TEST

The new freezing test was designed to alleviate the problems previously mentioned. As a result, the following objectives were established:

a. The test should be as simple as possible so that highway and geotechnical laboratories could readily conduct the test and obtain reproducible results. Complexities in the test should be diminished by automating the test as much as possible.

b. The test equipment must be reliable.

c. The test must be of short duration.

d. The test must accommodate the complete range of material types; in particular, it must accommodate granular base and subbase materials as well as fine-grained subgrade materials.

e. The test apparatus should be relatively inexpensive to construct and operate.

f. The test must relate to frost heave and thaw weakening in the field.

g. The test should be readily modified so that actual field conditions could be simulated if desired.

Several of the test parameters critical to satisfying these objectives were developed. They include:

a. Controlling the boundary temperatures precisely.

b. Minimizing radial heat flow.

c. Minimizing side friction.

d. Providing free access to water.

e. Allowing for freeze-thaw cycling.

f. Accounting for both frost heave and thaw weakening.

g. Limiting the test to 1 week.

The literature on freezing tests was thoroughly reviewed for state of the art practices. In addition, the author was able to draw upon his considerable experience in conducting soils freezing tests. As a result, it was proposed that the new freezing test include the following features:

a. The basic cell should be of the multi-ring type with a rubber membrane liner.

b. The upper and lower boundary temperatures should be controlled by circulating liquid from programmable, refrigerated circulating baths through heat exchange plates.

c. A temperature controlled cabinet or room capable of maintaining an ambient temperature of 1°C for four samples should be included.

d. The samples should have fixed surcharges.

e. A constant-head source of water fixed at the bottom of the samples should be available.

f. The test would employ two freeze-thaw cycles of 2 days duration each.

g. The test should use heave rate as an index of frost heave susceptibility.

h. The CBR test should be used as an index of thaw weakening susceptibility.

i. The entire test should be automated through a computerized data acquisition and temperature control system.

A completion discussion of the development process for the new freezing test is given by Chamberlain (1986).

5. DESCRIPTION OF THE FREEZING TEST

5.1 Apparatus

The new freezing test imposes freeze-thaw cycling on four samples, 150 mm (6 in.) in diameter, and 150 mm (6 in.) in height. The samples are confined in containers made up of Plexiglas rings lined with rubber membranes. Water is freely available through porous base plates. Figure 4 illustrates the arrangement.

Cold plates are located directly on top of the samples and beneath the porous bases. The top and base plates are connected in series in two separate circuits. Ethylene glycol-water solutions are circulated through the cold plates from two refrigerated circulating baths to control the end temperatures. Bath 1 is connected to the top plate circuit, bath 2 to the base plate circuit.

A surcharge of 3.5 kPa (0.5 lb/in.^{2}) is placed on top of the upper cold plate to simulate the weight of a 150-mm (6-in.) thick asphalt con-

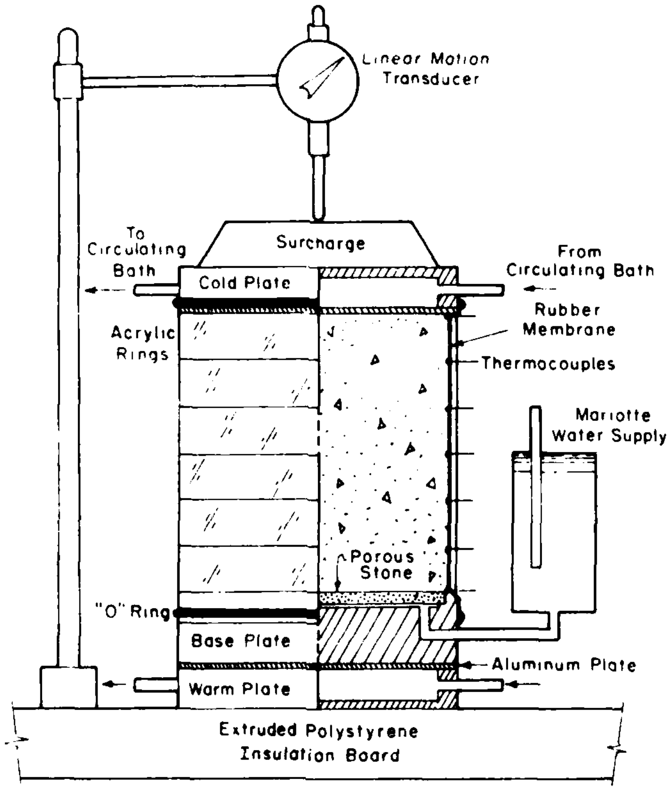

Figure 4. Sample assembly for the new freezing test.

crete pavement surface. A dial gauge and a Direct Current Differential Transformer (DCDT) are arranged on top to follow the frost heave and thaw settlement. Thermocouples are placed into the side of the sample to allow the freezing process to be followed.

Each sample is provided with a constant-head water supply that provides a controlled source of water during freezing, and which also provides a means for saturating the samples before freezing.

Four samples can be tested at the same time in the modified freezer chest (Fig. 5). The freezer chest provides an ambient temperature just above the freezing point of water so that radial heat flow is minimized.

The entire freezing and thawing process and the data gathering are accomplished automatically through the use of an inexpensive data acquisition and control system. Figure 6 illustrates the entire test setup. Details on assembling all the parts of this setup are given in Appendix A.

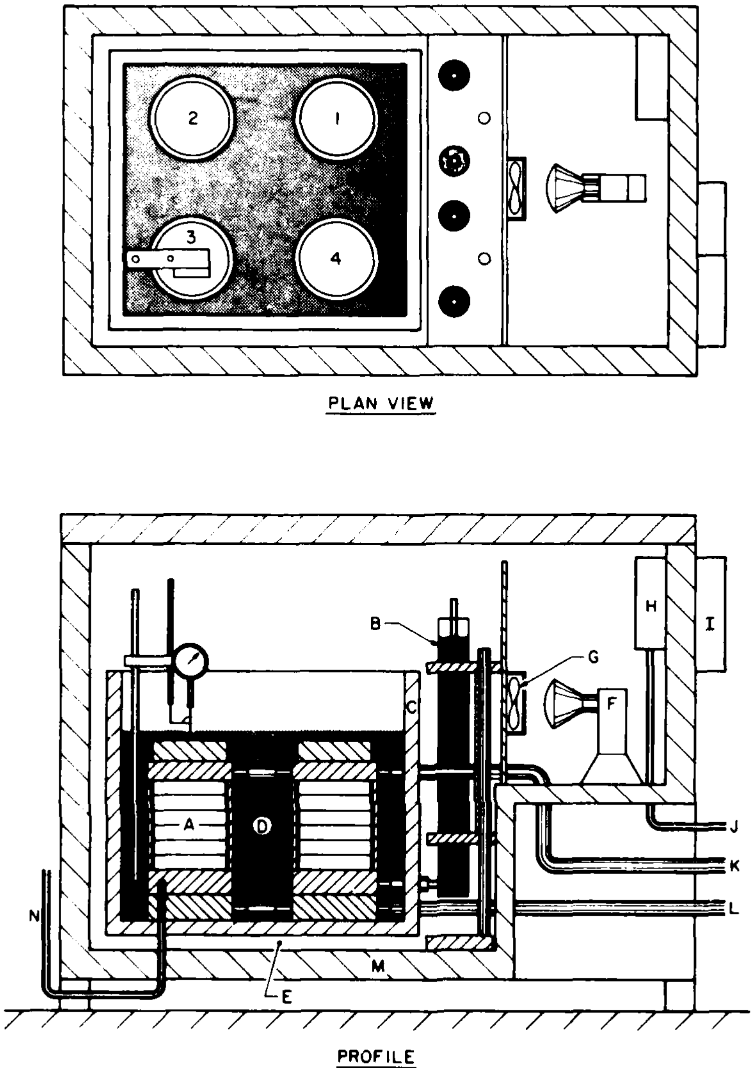

Figure 5. Freeze cabinet assembly for the new freezing test (A = sample assembly, B = water supply, C = rigid insulation, D = loose insulation, E = air space for temperature control, F = heat source, G = fan, H = thermocouple and DCDT output panel, I = temperature control unit, J = electrical leads to data logger, K = circulation lines from top cold plate to refrigerated circulating bath, L = circulation lines from bottom cold plate, M = freezer chest, N = drainage lines).

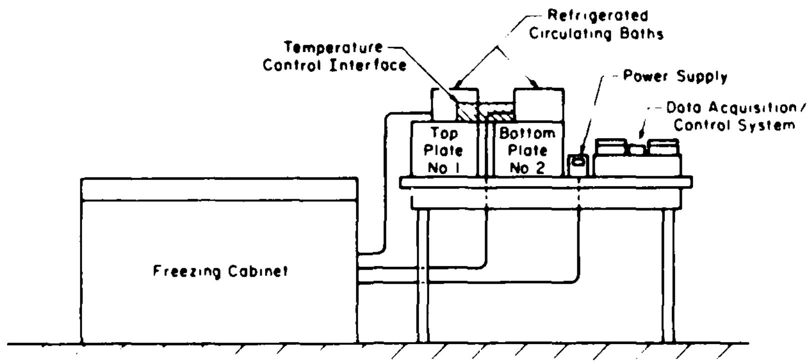

Figure 6. Complete setup for the new freezing test.

5.2 Data acquisition and control system

The data acquisition and control system consists of a computer controller, a data acquisition and control unit, a thermal printer and a digital cassette drive (Fig. 7).

The data acquisition unit is set up for making 36 single-ended dc-voltage readings from the thermocouples and 5 double-ended dc-voltage readings from the four DCDTs and the single power supply. Circuit diagrams showing the thermocouple and DCDT connections to the data logger are given in Appendix B, as are the data logger multiplexer card settings.

Two channels are dedicated to controlling the temperatures of the circulating baths. The two channels allow the selection of one of four pairs of set point temperatures in the refrigerated baths. Details on this are also given in Appendix B.

The data acquisition and control unit is controlled with a small, hand-held computer (an HP41CX calculator). All the necessary programs are stored on a tape cassette and are readily accessed by the computer from the cassette drive. The cassette drive also provides a storage medium for the data accessed during the test.

The computer has a built-in time base that is used to control the sequence of data taking and temperature cycling. Programs are provided to test the setup and calibrate the thermocouples before freezing, and to take and reduce the data during the test and to provide the temperature control. Annotated listings of the programs are provided in Appendix C. The thermal printer provides a hard copy of all the reduced data.

The entire system is battery operated, but is set up to operate normally on line voltage. Short-term power failures will not affect the

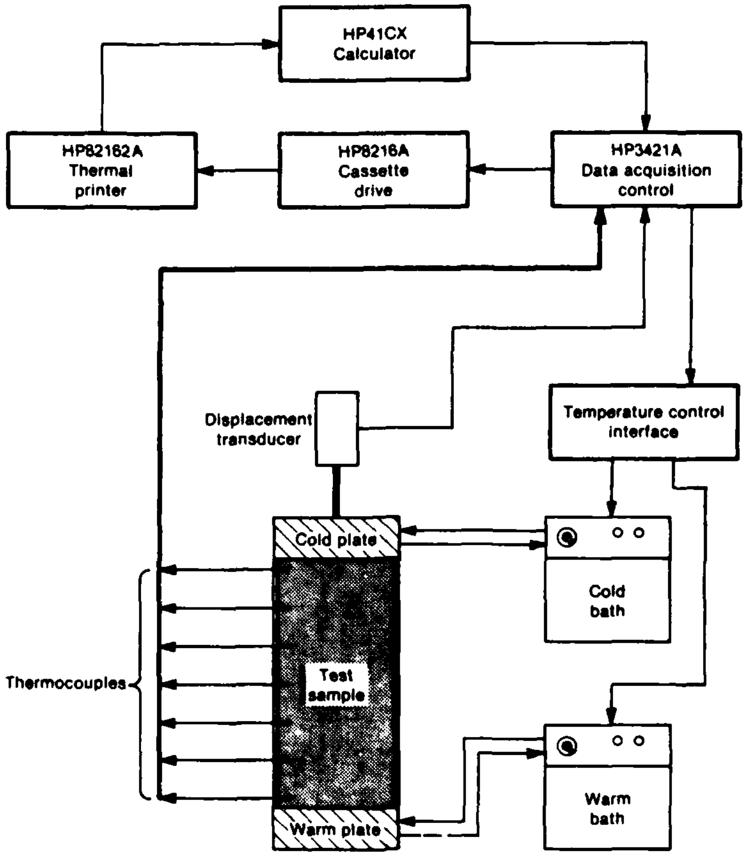

Figure 7. Schematic for the data acquisition and control system.

data acquisition and control process (power failures will, however, affect the operation of the refrigerated circulating baths and the freezing cabinet).

5.3 Freeze-thaw test

This test imposes two freeze-thaw cycles on the four samples placed in the freezer chest. Each leg of the two freeze-thaw cycles requires 1 day. The entire freeze-thaw cycling program requires 5 days, including an initial day of conditioning. Table 2 and Figure 8 show the boundary temperature settings during the freeze-thaw cycling period.

Each freezing leg consists of two different boundary temperature conditions. The first 8 hours of freezing is accomplished with an upper cold plate temperature of -3°C and a lower cold plate temperature of 3°C. The next 16 hours of the 24-hour freeze period is run with boundary tempera-

Table 2. Boundary temperature conditions for the new freeze test.

Day	Elapsed* time (hr)	Bath 1 (top temp.) (°C)	Bath 2 (bot. temp.) (°C)	Temperature selector position†
1	0	12	13	T_2
	16	3	3	T_0
2	24	-3	3	Bath
	32	-12	0.0	T_1
3	48	12	3	T_2
	64	3	3	T_0
4	72	-3	3	Bath
	80	-12	0.0	T_1
5	96	12	3	T_2
	112-120.5	3	3	T_0

*After running program has been started.
†For manual operation and making temperature adjustments.

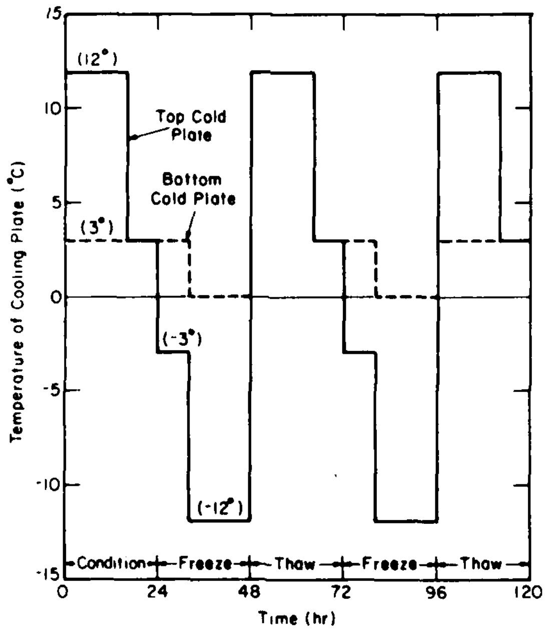

Figure 8. Boundary temperatures for the new freezing test.

tures of −12° and 0.0°C. The purpose of this freezing method is to impose freezing rates that are similar to those that occur naturally within a normal work day and to completely freeze the samples within 24 hours.

Complete freezing is necessary to thoroughly condition the material with frost action prior to freezing it a second time. The heave rates for materials containing clay fines may be increased significantly by freeze-thaw cycling. This procedure is designed to reveal any sensitivity of the frost heave rate to repeated freezing and thawing.

The thawing legs of the freeze-thaw cycles begin with the upper boundary temperature fixed at 12°C and the lower boundary temperature set at 3°C. After 16 hours, the upper boundary temperature is lowered to 3°C and both ends are held at 3°C for the remainder of the 24-hour thaw period. These thaw period boundary temperatures were selected to ensure the complete thawing of the frozen samples. The same boundary temperatures are applied during the conditioning period preceding the first freeze. The purpose of doing this is to ensure identical temperature profiles within the samples prior to both freeze legs.

Because of time constraints, only two freeze-thaw cycles are imposed. To make this test more readily acceptable, the time allowed for freezing and thawing is restricted to 1 week. Additional freeze-thaw cycling would be only of use in clay soils as most of the changes in structural properties that affect heave rate occur during the first freeze in most other soils.

Frost heave rates after 8 hours into each freezing leg are labeled critical heave rates and are used to determine the frost heave susceptibility of the material. Details on how to determine the frost susceptibility are given later in this report.

After the second thaw, the test samples are subjected to the CBR test and are sliced to determine moisture content profiles. The CBR test data are used to determine the thaw weakening susceptibility.

The overall frost susceptibility determination is based on an analysis of all the heave rate and thaw CBR data and knowledge of specific site conditions.

6. SETTING UP THE TEST

6.1 Initial setup procedures

The computer programs (Appendix C) used during the setup procedures allow the scanning of the thermocouple (T/C) assemblies both to determine that they are functioning properly and to calibrate each T/C for zero shift. These programs also allow the scanning of the frost heave transducers (DCDTs) for proper functioning and the circulating bath temperatures for proper settings. One of these programs is also used to initialize a cassette tape for recording the test data.

6.1.1 Loading the setup programs

a. Place the cassette marked NEW FREEZE in the cassette drive, label side up and tape end in first.

b. Turn on the cassette drive to STANDBY mode.

c. Turn on the thermal printer to STANDBY and MANUAL modes.

d. Turn on the data logger and computer.

e. Clear memory by pressing ←/ON .

f. Load the setup programs into the computer by pressing the following key sequence:

(1) α FR1α.

(2) XEQ α READP α.

The setup programs will be automatically loaded. Approximately 1 minute and 10 seconds is required. Wait for the display to show the numerical configuration before proceeding.

6.1.2 Adjusting the reference junction

a. Make a reference temperature ice bath in a thermos bottle with crushed ice and distilled water. Make sure that the crushed ice completely fills the thermos bottle before filling it with water.

b. Bundle all 36 thermocouples and the REF thermocouple together with rubber bands and insert them approximately 3 cm deep into the ice bath. Care should be taken to make sure that the tips of all thermocouples are within 1 cm of each other.

c. Wait approximately 30 minutes for the temperature to equilibrate.

d. Execute the program to set the reference junction by pressing the keys:

(1) USER on.

(2) Σ+.

e. The average reading for the thermocouples will be printed out.

f. Adjust the trim pot on the reference junction to increase (counterclockwise) or decrease (clockwise) the average reading.

g. Repeat steps d through g until the average reading is within ± 0.03°C.

6.1.3 Calibrating the thermocouples

a. Calibrate the T/Cs after the reference junction has been properly adjusted.

b. Make sure that the ice bath is fresh.

c. Execute the thermocouple calibration program by pressing the following key sequence:

(1) USER on.

(2) LN.

d. You will be prompted for the following information:

(1)	SERIES NAME?	Respond with a six digit alpha-numeric name followed by the R/S key for each question.
(2)	SAMPLE 1 NAME?	
(3)	SAMPLE 2 NAME?	
(4)	SAMPLE 3 NAME?	
(5)	SAMPLE 4 NAME?	
(6)	NO. OF SCANS?	Enter 6 followed by R/S.
(7)	SCAN INT?	Scan interval in HH.MMSS format followed by R/S; defaults to 30 minutes if only R/S is pressed.
(8)	START DATE?	Enter date in MM.DDYYYY format followed by R/S; defaults to current date if only R/S is pressed.
(9)	START TIME?	Enter time in HH.MMSS format followed by R/S; defaults to current time plus 10 seconds if only R/S is pressed.

e. Wait for the desired number of scans to be completed. Upon completion of six scans, the readings for each T/C will be averaged and stored in the file TSAVE2 in the extended memory of the HP41CX calculator (computer). A copy of each scan and the average values will be printed on the thermal printer. An example is shown in Figure 9.

TIME= [illegible]
DATE= [illegible]
MAIN POST
TP 222
AVG TC ZEROS

BERG1

TP-1

DEPTH MM	TEMP DEG C
0.00	0.04
12.70	[illegible]
38.10	0.03
63.50	-0.04
88.90	4.39-03
114.30	4.39-03
139.70	-0.02
152.40	-0.06

MP-1

DEPTH MM	TEMP DEG C
0.00	-0.07
12.70	-4.39-03
38.10	-0.04
63.50	0.02
88.96	-0.05
114.30	-0.03
139.70	0.01
152.40	0.01

TP-2

DEPTH MM	TEMP DEG C
0.00	-0.07
12.70	-0.03
38.10	-0.02
63.50	-0.05
88.90	-0.04
114.30	-0.05
139.70	0.01
152.40	-0.04

MP-2

DEPTH MM	TEMP DEG C
0.00	0.06
12.70	0.03
38.10	-0.02
63.50	-0.03
88.90	-4.39-03
114.30	4.39-03
139.70	0.01
152.40	-0.02

COLD BATH= 0.04 DEG C
WARM BATH= 0.02 DEG C
AMBIENT= 0.01 DEG C
ICE BATH= -4.39-03 DEG C

END OF READING

Figure 9. Example of thermocouple calibration printout.

6.1.4 Initializing the tape cassette

It is important that the tape cassette be initialized only after the thermocouples have been calibrated because the SERIES NAME entered during the calibration procedure is used as the DATA FILE NAME on the tape. Initialize the tape as follows:

a. Place a fresh tape cassette in the cassette drive.

b. Press XEQ α NEWM α.

c. Respond to the prompt NEWM _ _ _ by pressing 001 (establishes space for one file); wait 3.5 minutes for completion of this operation.

d. Press USER on.

e. Press the 1/x key (establishes 16,000 data spaces on the cassette).

f. Wait about 10 minutes for completion of this operation.

g. Remove this tape, mark it with series name and place it in the storage compartment of the cassette drive.

6.1.5 Checking the bath temperatures

a. Temporarily connect together the two circulation lines from the cold bath with a straight connector.

b. Ensure that the bath thermocouples are in the adaptors in the outlet lines located just inside the freezer compartment. Use silicone rubber to seal.

c. Make sure that there is sufficient 50/50 ethylene glycol-water solution in each refrigerated bath to fill each reservoir to within 25 mm (1 in.) of the top of the unit.

d. Turn on the power and cooling system switches on each bath and put the local/remote switches in the local positions. Set main dial temperature to 0°C. When the heater lights begin to flicker, the set temperature is being controlled.

e. For systems with hand set temperature control:

(1) Set coarse dial to 3°C on both baths. When the heater lights flicker, make a scan of the bath temperatures by pressing:

(a) USER on.

(b) $\sqrt{X}$ Key.

Make adjustments to the coarse and fine dials until the temperature is obtained to within ±0.1°C of +3°C.

(2) Repeat procedure (1) during the freeze-thaw test to obtain the appropriate bath temperatures. Make fine adjustments every 15 minutes until the appropriate temperature is obtained.

f. For systems with set point temperatures located on the baths:

(1) Set the temperature selector switches to DIAL. Set the main dials to the appropriate temperatures as shown in Table 2. When the heater lights flicker, make a scan of the bath temperatures by pressing:

(a) USER on.

(b) $\sqrt{X}$ Key.

Make adjustments to the coarse and fine dials unitl the desired temperature is obtained to within ±0.1°C. Table 2 shows the correct temperature settings.

g. Repeat this procedure for each of the other three pairs of set temperatures, T_0, T_1 and T_2, using a fine screwdriver to make necessary adjustments to the small, slotted temperature-control potentiometers.

h. Do not use the fine temperature control to adjust the main dial temperature after T_0, T_1 and T_2 are set. The fine dial setting also affects T_0, T_1 and T_2. Use only the coarse dial to make further dial temperature adjustments.

6.2 Sample preparation

Because large-diameter undisturbed samples of soil and gravel materials are difficult to obtain, test samples are normally compacted in the laboratory to in situ density conditions. It is, thus, desirable to know the moisture and density characteristics of the subject materials before preparing the sample. With that understanding, the sample preparation procedure is as follows.

6.2.1 Data sheets

Prepare data sheets such as shown in Appendix D. Fill in all of the data, including the sample identification, sample specifications and the compaction mode.

6.2.2 Materials

Weigh out approximately 6000 g of the soil. It is not necessary to dry the soil first unless the water content is greater than desired. Mix well and determine the water content on a 100-g sample. Adjust the moisture content of the remaining material to the desired value and allow the sample to condition overnight in a closed container.

6.2.3 Molds

Select six Plexiglas rings and a rubber membrane. Make sure that two of the rings have grooves cut into one edge. Tape the splits tightly closed with filament tape. Stretch the rubber membrane and make sure that there are no holes or defects. Weigh the rings, membrane and the Plexiglas base disk together and record the results.

While the material is conditioning, set up the sample mold. First, place one of the three steel side plates into the cavity on the steel base plate. The tops of the side plates are marked "T." Next, place the Plexiglas base plate with a rubber membrane wrapped around it into the bottom of the mold. The rubber membrane should lie collapsed on top of the Plexiglas base. Then, place a second side plate on the base, fitting it snugly against the first. Next, place the Plexiglas rings into the mold, one at a time. The thermocouple holes in the rings must be aligned vertically. The top and bottom rings have grooves cut in them to accommodate thermocouples at the sample ends. These grooves must be positioned facing the ends. The mold assembly should now look as shown in Figure 10. After the six rings are in place, position the last side plate in place and bolt on the top steel plate. Pull up the rubber membrane and stretch it out at the top of the assembly and down over the corners of the top plate. Make sure that the membrane is tight and free of ripples. You are now ready to compact the sample.

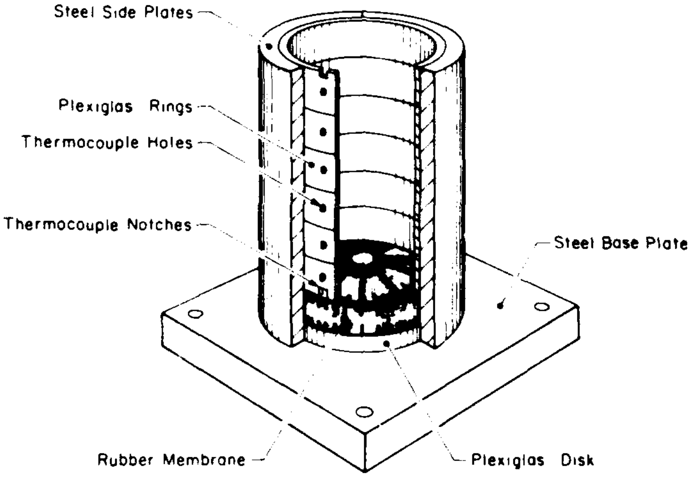

Figure 10. Compaction mold assembly.

6.2.4 Compaction

The test material is placed into the mold and compacted in five layers of equal thickness. The amount of soil and compaction effort will be determined by the dry density that you want. A modified Proctor hammer is preferred because the guide tube protects the rubber membrane from compaction damage. During compaction, make a water content determination on a 100-g subsample. Enter the information on the data sheet. Compact the sample level with the top of the uppermost ring. Fold up the rubber membrane and remove the compacted sample assembly from the steel mold.

6.2.5 *Sample property determination*

Weigh the sample, including the Plexiglas rings, the rubber membrane and the Plexiglas base. Enter the information on the data sheet and make calculations of the wet and dry unit weights, void ratio, porosity and degree of saturation.

6.3 Freezing point determination

The freezing point of the pore water in soils is commonly just below 0°C. However, fine-grained soils and coarser-grained soils containing salts may have lower freezing points. The freezing point can be determined by placing a thermocouple in a small amount of test material in a test tube and observing the temperature changes during freezing. The soil should be placed in the test tube at a water content that is equivalent to 90 to 95% saturation for the selected dry density. Figure 11 illustrates the arrangement. Cold bath 1 can be used to induce freezing. Use the following procedure:

a. Set the cold-bath-1 temperature selector switch to the bath position (-3°C) and local/remote switch to local.

b. Fill a clean test tube with 1 cm of wet soil and press.

c. Center the thermocouple and press another 1 cm of soil around it.

d. Immerse the test tube in the -3°C ethylene-glycol solution.

e. Observe temperature with time.

f. Record the steady-state freezing point depression temperature that occurs after nucleation (Fig. 12).

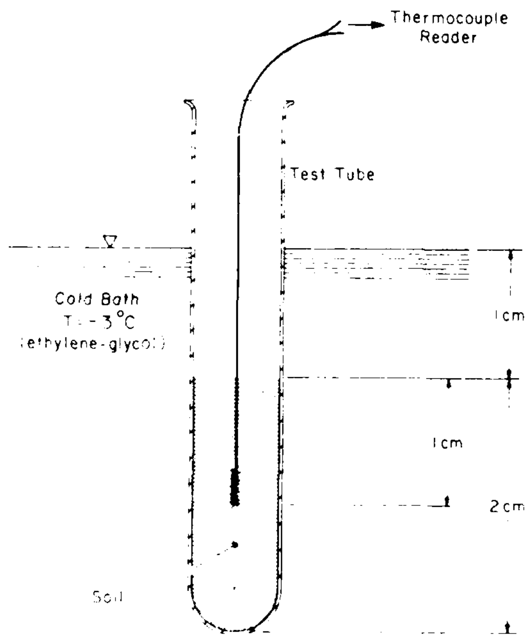

Figure 11. Setup for determining the pore water freezing temperature.

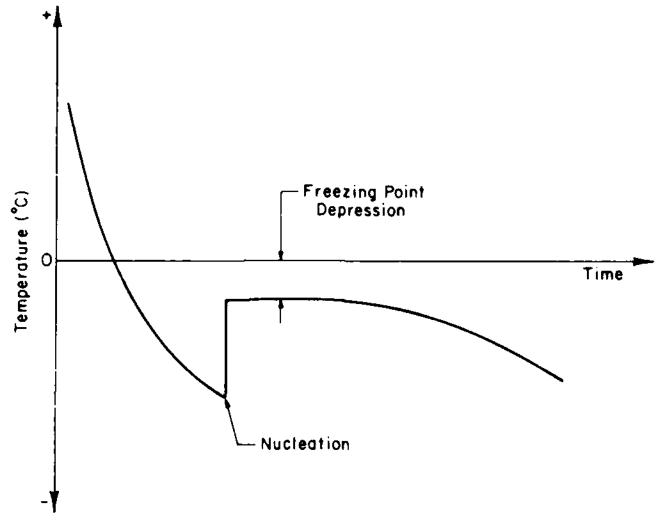

Figure 12. Selecting the freezing point depression from the cooling curve.

g. Thaw the sample, remove the thermocouple and determine the soil water content.

h. Place the thermocouple in the ice bath and read the temperature.

i. Subtract the ice bath reference temperature from the measured freezing point depression temperature to obtain the adjusted freezing point depression.

The freezing point depression temperature obtained with this procedure is used for two purposes. The first is to allow the set point temperatures of the refrigerated bath to be adjusted. If the freezing point depression is lower than -0.5°C, then the cold-side temperatures should be lowered by the amount of the freezing point depression. For example, if the freezing point depression is -1°C, then T_{BATH} on refrigerated bath 1 should be lowered to -4°C and T_1 to -13°C. The freezing point depression is also used to estimate the position of the freezing isotherm and is input into the running program when the FREEZE TEMP? prompt appears.

6.4 Final setup procedures

6.4.1 Mounting the samples

Roll the rubber membrane over the outside of the Plexiglas rings at both ends of the sample assembly. Place a piece of thin plastic film (Saran wrap) and a Plexiglas disk over the top end to prevent evaporation. Place a piece of filter paper on the porous stainless steel disk in the base assembly, and position the sample on the base so that the thermocouple holes are located on the surface farthest away from the post that carries the dial gauge and DCDT. Roll down the rubber membrane over the base and seal with heavy rubber bands or O-rings (Fig. 4).

6.4.2 Placing the samples in the freezer

Position each of the sample assemblies atop of the cooling plates located at the bottom of the freeze compartment so that the posts are located in the corners and the thermocouple holes are located toward the center of the box. Figure 5 shows the sample numbering order. Record the location of each sample. Connect the inlet and outlet water lines to each sample base. Place a surcharge weight on top of each sample.

6.4.3 Preparing the saturation

Make sure that the inlet and outlet water lines for each sample are clamped off. Fill the water supply tubes with water (preferably distilled water) and position the top caps with the long bubble tubes attached. A little vacuum grease will ensure a good seal. Loosen the brass nut sealing the bubble tube and lower it until the tape mark is flush with the top of the fitting. Clamp the small-diameter drain line located on the outside left side of the freezer and open both the inlet and outlet clamps on the water lines leading to and from the samples. Disconnect the small-diameter drain line from the T-connector located on the side of the freezer, open the clamp and allow water to drain into a dish or pan until air is completely purged from the system. Close the clamp and reconnect the drain line to the T-connector. The water pressure level is now at approximately 25 mm (1 in.) above the base (both the bottom end of the bubble tube and open end of the T-connector are at this level). Repeat this procedure for each sample. You are now ready to saturate.

6.4.4 Saturating the samples

Begin saturation at the start of a work day. Raise the bubble tubes in each water supply 25 mm (1 in.) per hour until excess water appears on the upper surfaces of the samples or until 8 hours have passed. Then lower the bubble tubes to the 152-mm (6-in.) level for another 16 hours. After the 24-hour saturation period is complete, lower the bubble tubes to the 1.0-mm (0.5-in.) level and open the clamps on the drain lines outside the cabinet. The next step is to insert the thermocouples.

6.4.5 Inserting the thermocouples

Each sample is instrumented with eight thermocouples (T/Cs). The T/Cs are numbered 1 through 8 and each set is numbered 1,2,3 or 4. The T/Cs are placed in the sides of the samples with the number 1 T/C located at the top. Place the bottom T/C first and work up. Dip the tip of the T/C into silicone rubber and push the sharp end through the ring and rubber membrane into the sample, about 6.5 mm (0.25 in.) as shown in Figure 13. Puncturing the membrane with the end of a paper clip will make this procedure easier in some cases. After placing all the T/Cs, dab a little silicone rubber on the place where the T/Cs penetrate the Plexiglas rings. Plug the T/Cs into the junction box, observing the proper order as marked. You are now ready to complete the test assembly.

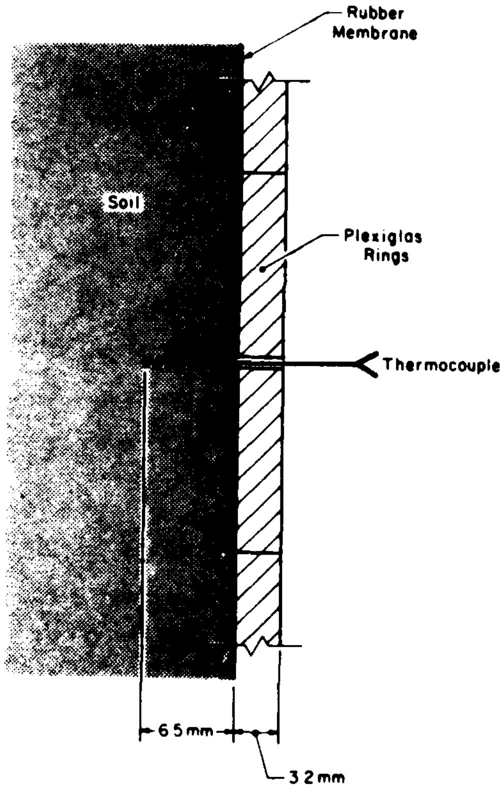

Figure 13. Location of thermocouples in the sample.

6.4.6 Completing the test assembly

Remove the lead weights and plastic disks from the top of the samples. Place the cold plate assemblies on top of the samples and fold up the rubber membranes to overlap the cold plates and clamp and seal with rubber bands (Fig. 4). Connect the lines from the refrigerated bath to the upper cold plate assembly. Place the lead surcharge weights on the cold plates and center. Place the DCDT and dial gauge assemblies on the aluminum rods and lower and center the dial gauges so that they read 0.00 in. Plug the DCDTs into the appropriate terminals on the junction box and proceed to check their operation.

6.4.7 Checking operation of DCDTs

Turn on the computer, thermal printer, cassette drive, data logger and power supply and press the following keys:

a. USER on.

b. LOG.

The DCDT readings will be printed out on the thermal paper. Proper readings will range between -30 and -20 mm. Check connections and make necessary adjustments if the readings are unacceptable. If DCDTs are working properly, proceed to instructions for starting the freezing test.

7. CONDUCTING THE TEST

The computer programs used for running the freeze test allow the periodic scanning of the test data, the automatic control of the boundary temperatures, reduction and analysis of the data, printing of the results on the thermal paper and recording the results on a tape cassette. The last data scan will be made at 120.5 hours, at which time the critical heave rate data will be summarized and the logging and control system will automatically shut down. The program flow chart is shown in Figure 14. An example of the data printout is given in Appendix D. Begin the freeze test by loading the running programs as follows.

7.1 Loading the running programs

a. Place the cassette marked New Freeze in the cassette drive.

b. Turn on the cassette drive to standby mode.

c. Turn on the thermal printer to standby and manual modes. Make sure that the paper supply is full.

d. Turn on the data logger and the computer.

e. Clear the main memory by pressing:

(1) α ALAMAZ α.

(2) XEQ α PCLPS α.

f. Load the data logging and temperature control programs into the computer by pressing the following key sequence:

(1) α FRST α.

(2) XEQ α READP α.

The programs will be automatically loaded. Approximately 3.5 minutes is required. Wait for the display to show a numerical configuration before proceeding.

g. Proceed to instructions on starting the test.

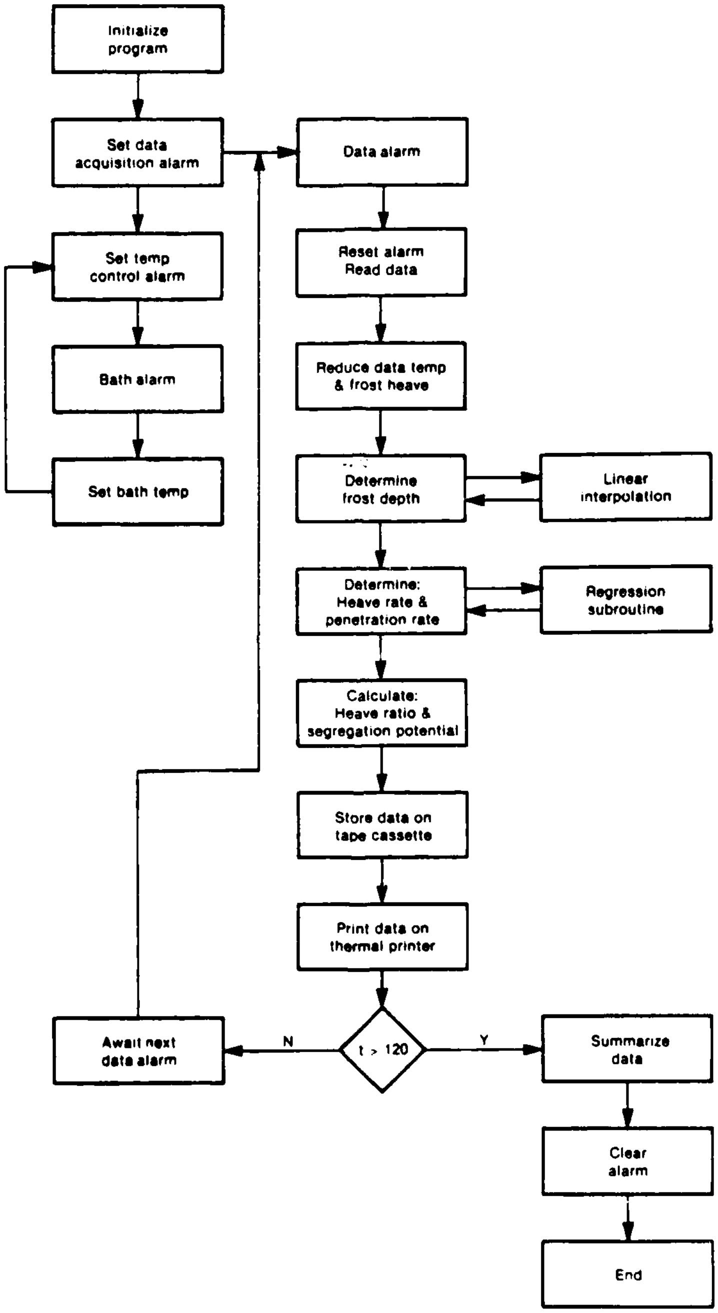

Figure 14. Flow chart for data acquisition and temperature control program.

7.2 Starting the test

a. Place the data cassette tape into the cassette drive.

b. Start running the programs by pressing:

(1) USER on.

(2) LN.

c. The HP41CX calculator will then prompt you for test information as follows:

(1) SERIES NAME? (2) SAMPLE 1 NAME? (3) SAMPLE 2 NAME? (4) SAMPLE 3 NAME? (5) SAMPLE 4 NAME?	Respond to each question with no more than seven alphanumeric characters followed by pressing the R/S key.
(6) CONTROL T?	Enter Y if computer controls the temperatures, N if not.
(7) FREEZE TEMPERATURE?	Enter the freezing point of the pore water in degrees Celsius by pressing the R/S key.
(8) DATE?	Respond with the appropriate date in MM.DDYYY format, followed by the R/S key; defaults to the current date if only R/S key is pressed.
(9) TIME?	Respond with the desired start time in HH.MMSSS format followed by the R/S key; defaults to the current time plus one minute if only R/S key is pressed.

d. Data scanning will begin automatically upon pressing the R/S command. Data scans are made every 1 hour unless another period is selected later. An example is shown in Figure 15.

e. Data scans can be made at other times by pressing:

(1) USER on.

(2) Σ + .

```
...............
TIME  17.43
DATE  4.271984
Σ TIME:  32.0006 HOURS
...............

BERG1

TP-1

      DEPTH TEMP.
      MM    DEG C

       0.00 -2.54
      12.70 -1.93
      38.10 -0.82
      63.50  0.09
      88.90  0.74
     114.30  1.53
     139.70  2.34
     152.40  2.72

FROST PEN.= 60.9 MM
FROST HEAVE= 0.2 MM
PEN. RATE= 20.0 MM/DAY
HEAVE RATE= 0.0 MM/DAY
HEAVE RATIO= 0.04
SEG. POT.= 93.2 MM2/
           DEG C-SEC

TP-2

      DEPTH TEMP.
      MM    DEG C

       0.00 -2.67
      12.70 -1.04
      38.10 -0.40
      63.50  0.55
      88.90  0.00
     114.30  1.79
     139.70  2.41
     152.40  2.83

FROST PEN.= 49.9 MM
FROST HEAVE= 0.2 MM
PEN. RATE= 24.5 MM/DAY
HEAVE RATE= 0.6 MM/DAY
HEAVE RATIO= 0.02
SEG. POT.= 59.2 MM2/
           DEG C-SEC

MP-1

      DEPTH TEMP.
      MM    DEG C

       0.00 -2.04
      12.70 -1.55
      38.10 -0.49
      63.50  0.19
      88.90  0.94
     114.30  1.61
     139.70  2.20
     152.40  2.06

FROST PEN.= 56.4 MM
FROST HEAVE= 0.7 MM
PEN. RATE= 47.4 MM/DAY
HEAVE RATE= 1.2 MM/DAY
HEAVE RATIO= 0.03
SEG. POT.= 194.5 MM2/
           DEG C-SEC

MP-2

      DEPTH TEMP.
      MM    DEG C

       0.00 -2.24
      12.70 -1.56
      38.10 -0.69
      63.50  0.00
      88.90  0.71
     114.30  1.42
     139.70  2.17
     152.40  2.34

FROST PEN.= 60.8 MM
FROST HEAVE= 0.7 MM
PEN. RATE= 23.8 MM/DAY
HEAVE RATE= 1.9 MM/DAY
HEAVE RATIO= 0.00
SEG. POT.= 264.1 MM2/
           DEG C-SEC

COLD BATH= -2.92DEG C
WARM BATH=  3.11DEG C
AMBIENT=  1.13DEG C
ICE BATH=  0.00DEG C

TAPE POINTER=  3,240.00
```

Figure 15. Example of test results for a single scan.

This intermediate data scan option will not respond if a programmed scan is scheduled within the next 8 minutes. The message, WAIT FOR SCHEDULED SCAN, will be seen on the display and the thermal printer type. DO NOT INTERRUPT A SCAN IN PROGRESS — WAIT UNTIL THE FULL SEQUENCE OF DATA LOGGING, PRINTING ON THE THERMAL PAPER, AND RECORDING ON THE TAPE CASSETTE IS COMPLETE.

f. Proceed to nucleation instructions.

7.3 Nucleation

a. The first 24 hours is a tempering period. After 24 hours has elapsed since starting the test, the first freezing cycle will begin. At approximately 24.5 hours, make a data scan by putting USER on and pressing √X. If the top thermocouple readings are 1.0°C lower than the freezing point of the soil water, enable nucleation by opening the freezing cabinet and delivering two sharp blows to the tops of each cold plate through the aluminum rod. Scan the data once more. The top thermocouple temperature will rise if nucleation occurred. Other evidence of nucleation may be positive frost heave rates on the printouts. Repeat this process for additional 0.5°C drops in the top thermocouple temperatures until nucleation is achieved.

b. Repeat the nucleation procedure for the second freeze-thaw cycle, which begins at 72 hours.

c. Proceed to observing the test instructions.

7.4 Observing the test

a. Ensure that boundary temperatures are correct. If the temperatures are set manually, then adjust the dials on the baths. Clockwise turns increase the temperature; counterclockwise turns decrease the temperature. If the temperatures are being controlled automatically, then no adjustments can be made (except to MAKE SURE THAT THE BATH TEMPERATURE DIAL IS SET TO 15°C OR GREATER).

The bath temperatures can be scanned by pressing:

(1) USER.

(2) √X.

b. Make sure that the thermocouple reference has not drifted. If the ice bath temperature reported on the data printout is greater than 0.06°C, then the ice bath may need to be remade. If the ice bath is good, then adjust the reference junction to within ±0.03°C of 0.0°C.

The ice bath temperature can be scanned by pressing:

(1) USER.

(2) √X.

c. Ensure that the ambient temperature is maintained between 0° and 1°C. The ambient temperature can be observed by pressing:

(1) USER.

(2) √X.

d. Check that the thermal printer has an adequate supply of paper. Approximately three rolls of paper are needed for each test. Particular attention should be given to ensuring that there is a fresh roll of paper at the beginning of a freeze cycle, especially if the test is to run unattended for more than 24 hours. After replacing tape, press XEQ α PRA α to make sure that the printer is working properly. If the printer runs out of tape, the entire scanning and temperature control procedure will be interrupted.

e. Ensure that the cassette tape has sufficient space available. The TAPE POINTER location printed out at the end of each data listing indicates how many data spaces have been used. The scheduled data scans require 9000 data spaces on the tape; 16,000 data spaces are available on the tape, which allows space for 7000 intermediate pieces of data (72 per scan) or approximately 100 extra scans.

f. The sample bases need to be purged of air, particularly after a thaw. To do this, disconnect and lower the drainage lines located outside the freezing cabinet and allow them to drain until air bubbles cease to appear. If a large amount of air is present, a slight suction applied by mouth to the drain hose should start the flow. Refill the water supply if necessary, after purging the sample bases of air.

g. Make sure that the water supply tubes are adequately filled and are operating correctly.

h. Make and record dial gauge readings, particularly at the ends of freezing or thawing legs, and compare what you see with the frost heaves recorded on the thermal paper. These readings should agree to within ±0.2 mm, as both the dial gauge and DCDT transducer are mechanically linked.

7.5 Completing the test

The last data scan will occur at 120.5 hours. The computer is programmed to print END OF TEST and to summarize the heave rate data for both freeze cycles on the thermal printer paper (Fig. 16). The entire data logging system will then shut down automatically. Disassemble the apparatus as follows.

a. Make and record dial gauge readings. Check to see if they are in agreement with frost heaves.

b. After the data logging system has shut down, turn off the refrigerated circulating baths and the freezing cabinet.

END OF TEST

TEST SERIES BERG1

CRITICAL FROST HEAVE
RATES , MM/DAY

SAMPLE ID	FREEZE NO	8 HOURS	16 HOURS
TP-1	1	0.8	4.5
	2	7.6	8.2
TP-2	1	0.6	4.6
	2	8.4	9.2
MP-1	1	1.2	8.5
	2	2.7	8.0
MP-2	1	1.9	8.2
	2	2.6	8.7

Figure 16. Example of summary printout at the end of a test.

c. Remove dial gauge and DCDT assemblies.

d. Remove surcharge weights.

e. Remove cold plate assemblies as follows: clamp off the two plastic tubes leading to the refrigerated circulating bath from cold plates 1 and 4. Then disconnect the two tubes from the cold plates, being careful not to spill the ethylene-glycol solution. Use a short piece of plastic tubing to temporarily connect the two cold plate assemblies as a unit.

f. Remove enough of the loose insulation to allow access to the thermocouple assemblies and water lines.

g. Remove the thermocouples from the sides of the samples by pulling each gently away from the Plexiglas rings.

h. Clamp the water lines and disconnect the plastic tubes from the base of each sample.

i. Remove each sample assembly, complete with each base.

j. Proceed to instructions for CBR test.

7.6 <u>Conducting the CBR test after thawing</u>

Conduct the CBR test immediately after 120.5 hours have elapsed.

a. Remove the samples from the bases and carefully place them in plastic bags and seal tightly. One at a time, remove the plastic bags and carefully place the samples on an aluminum pie plate of known tare weight. Weigh the sample and the pie plate. Slide a 150-mm (6-in.) diameter hose clamp over each ring and tighten. The hose clamps restrain expansion of the Plexiglas rings during the CBR test.

b. Remove the plastic film from on top of the sample.

c. Conduct the CBR test using standard procedures, but limiting the penetration to 7.6-mm (0.3-in.) depth. Record the results.

d. Take a small water content sample from the area where the CBR piston penetrated the wall. Determine wet and dry weights and water content.

e. Remove the hose clamps, rings and rubber membrane from the sample and cut it into six equal slices. Determine the water content of each slice. Also determine weight of the water left in the pie pan.

7.7 Presenting the data

a. Enter the series and sample names on the data sheet provided (Appendix D). Record also the compaction water content, dry density, porosity, and degree of saturation and freezing point depression.

b. The final printout of the data will summarize the frost heave rates during each freeze-thaw cycle. Check to see if these data agree with what was recorded on the thermal paper during the test. Record these data on the data sheet.

c. Plot the frost heave and frost penetration versus time on the data sheet. Check to ensure that the heave rate calculations are accurate.

d. Record the before and after freezing and thawing CBR values on the data sheet along with the corresponding water contents.

e. Plot the before and after freezing and thawing water content profiles on the data sheet.

7.8 Determining the frost susceptibility

Use the two heave rates and the CBR values to determine the frost susceptibility. As this test is only currently under development, exact criteria have not been established. Further correlations with field observations must be made. However, tentative frost susceptibility criteria are given in Table 3.

Compare the 8-hour frost heave rates observed during the first and second freeze-thaw cycles with each other. If there is a significant increase (or decrease) during the second freeze, as there is in the example shown in Figure 17, then the heave rate value selected will depend on the location of the construction site. If the site is in a very temperate region where many freeze-thaw cycles occur and the water table is near the zone of freezing and thawing, then the 8-hour heave rate during the second

Table 3. Tentative frost susceptibility criteria for the new freeze-thaw test.

Frost susceptibility classification	8-hour heave rate (mm/day)	Thaw CBR (%)
Negligible	<1	>20
Very low	1-2	20-15
Low	2-4	15-20
Medium	4-8	10-5
High	8-16	5-2
Very high	>16	<2

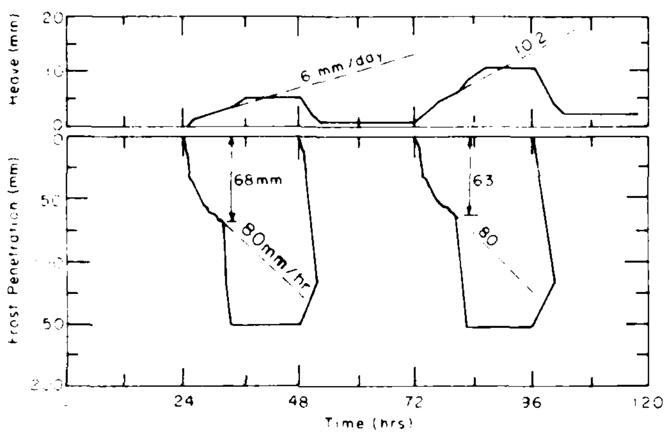

Figure 17. Example of the effect of freezing and thawing on frost heave rate.

freeze should be selected. If the site is in a more severe winter climate where the frost penetration is more continuous during the winter, then the 8-hour heave rate during the first freeze should be selected.

The heave rate criteria allow the determination of the frost heave susceptibility of a material that can be related to pavement roughness during the freezing period. The thaw CBR value allows the determination of the thaw weakening susceptibility of the material. Compare the thaw CBR value with the tentative criteria in Table 3 to determine the thaw weakening susceptibility. The actual thaw weakening criteria must be determined by the engineer and the design practice employed. At the moment, it does not appear useful to use the percent reduction in CBR as the thaw weakening criterion.

8. DISCUSSION OF TEST RESULTS

An example of the test results is shown in Figure 17. It can be seen for this case that the frost heave rate is much greater during the second freeze than during the first. This reveals the importance of conducting at least two freeze-thaw cycles. This does not always happen, but can be

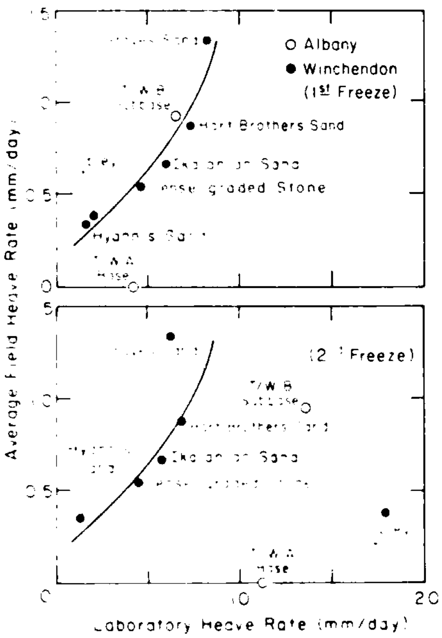

Figure 18. Correlation of laboratory and field frost heave rates.

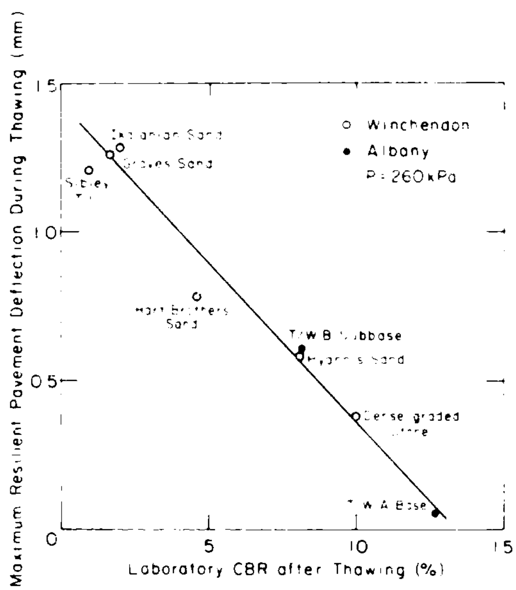

Figure 19. Comparison of laboratory CBR test results after freezing and thawing with field pavement deflection.

generally expected for soils containing a significant amount of clay-sized particles. As previously discussed, the decision on which of the two heave rates should be used for assessing the frost susceptibility depends primarily on site conditions. Figure 18 shows that, for the series of tests conducted to date with the new freezing test, the heave rates from first freeze correlate with the field observations. In all cases, the water table remained below the depth of cyclic frost penetration.

In many cases, the frost heave susceptibility will not be the controlling factor for determining the frost susceptibility of the material. Figure 19 shows a comparison of the CBR after thawing with the field pavement deflecton during thawing. It can be seen that for the Sibley till material, the thaw weakening was very high, whereas the heave rate during the first freeze (Fig. 18) was very low. Table 3 shows that the resulting frost susceptibility classification of this soil would be based on its thaw weakening susceptibility.

Because this test is conducted under rather severe conditions, it can be expected to err on the conservative side. To make it more descriminating, it is possible to conduct the test with conditions more nearly like field conditions. Adjusting the water table to a lower level would require the inclusion of a porous stone with a 1-atmosphere air entry value at the base. Increasing the surcharge would require additional weights on the surface of the test samples. These procedures can be accomplished with additional effort and hardware. However, it is recommended that less severe conditions of freezing be simulated by conducting the tests on unsaturated samples under the closed condition of no water supply. If tests are conducted with both the open and closed system freezing, then the limits of frost susceptibility of a soil can be determined.

9. CONCLUSIONS

The freezing test described here can be used to determine the frost susceptibility of soils and granular base materials. The determination of the frost susceptibility can be based on one of three factors: 1) the frost heave rate during the first freeze, 2) the heave rate during the second freeze, or 3) the CBR after the second thaw. The factor selected as controlling the frost susceptibility must be related to the site conditions.

The test can be conducted under very severe conditions of open water supply freezing or under closed system freezing. The actual site conditions should be considered before determining which test method is appropriate.

This test reduces the time for determining the frost susceptibility of a soil to half that needed for the standard test.

The test procedures should be followed closely to ensure repeatability and reliability. The automated test equipment removes much of the variability normally resulting because of human error. However, close attention to the details of sample preparation and test setup is still necessary.

Since any new test, such as the freezing test described in this report, requires a considerable amount of effort to establish its efficiency, it should be understood that this test needs further study. Ideally, it should be applied in the field under a wide range of conditions. To this end CRREL is willing to cooperate with transportation departments, universities, consulting firms and individuals interested in determining the frost susceptibility of granular soils used in road construction. This can be done by contracting with CRREL to conduct tests, by obtaining a set of shop drawings (which CRREL will provide) and by constructing the necessary equipment or by contracting with CRREL to provide the test equipment.

10. LITERATURE CITED

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APPENDIX A: ASSEMBLING THE APPARATUS

The test apparatus includes a freezer cabinet, four sample assemblies, four water supplies with drainage lines, four DCDTs, four sets of thermocouples, two refrigerated circulating baths, one data acquisition and control system, one temperature control interface, and one power supply.

The following instructions are for connecting the various parts and for making some initial control settings:

a. Set the freezer chest on the floor, leaving it on the wooden pallet. Plug it into a 20-A, 115-V circuit. Turn it on by setting the green switch on the lower right front of the chest to I and the yellow switch to S. You should hear the muffled hum of the compressor. In a few minutes you should notice the interior beginning to cool. Allow the chest to cool down for 24 hours. Proceed to the next step while the freezer is cooling.

b. Place a table of approximately 1.5 x 1 m (5 x 3.5 ft) dimensions to the left of the freezer. Place on the table the two circulating baths as shown in Figure 3. To the right of the circulating baths, place the data logging and control system and, to the rear of the data logger, put the power supply.

c. Check the operation of the refrigerated baths. Connect the inlet and outlet ports with a short piece of tubing. Plug the baths into two separate 20-A, 115-V circuits. Turn on both baths with the cooling system and heat switches. Turn the temperature selector switches to the DIAL positions and the local/remote switches to the local positions. Set the large dial to approximately -20°C and wait 30 minutes for the baths to cool. Use the thermometers positioned in the baths to ensure the proper response.

d. Connect the insulated circulation lines leading from the freezer chest to the refrigerated circulating baths. Make sure that bath 1 is connected to the top cold plates and bath 2 to the bottom cold plate, and that the inlet and outlet connections are made as marked.

e. Connect the temperature interface control box to the two cold baths with the two large cable connectors, as marked. Using the cable with a small connector on one end and three insulated wires on the other, connect the control box to terminal block 2 on the HP3421A data acquisiton unit. Connect the black wire to channel 20 low, the white wire to channel 21 low, and the red wire to channel 20 high. Connect channels 20 high and 21 high together with a jumper wire.

f. Connect cables 1, 2 and 3 to terminal blocks 0, 1, and 2 as shown in Appendix B.

g. Connect the power supply leads between the number 2 high and low terminals on terminal block 2 to the power supply, making sure the marked polarity is observed.

h. Set up the data acquisition and control system as shown in Figure 4, making sure that the labeled sequence of connections is made.

APPENDIX B: DATA ACQUISITION AND CONTROL SYSTEM

B1. Circuit connections for thermocouples and DCDTs

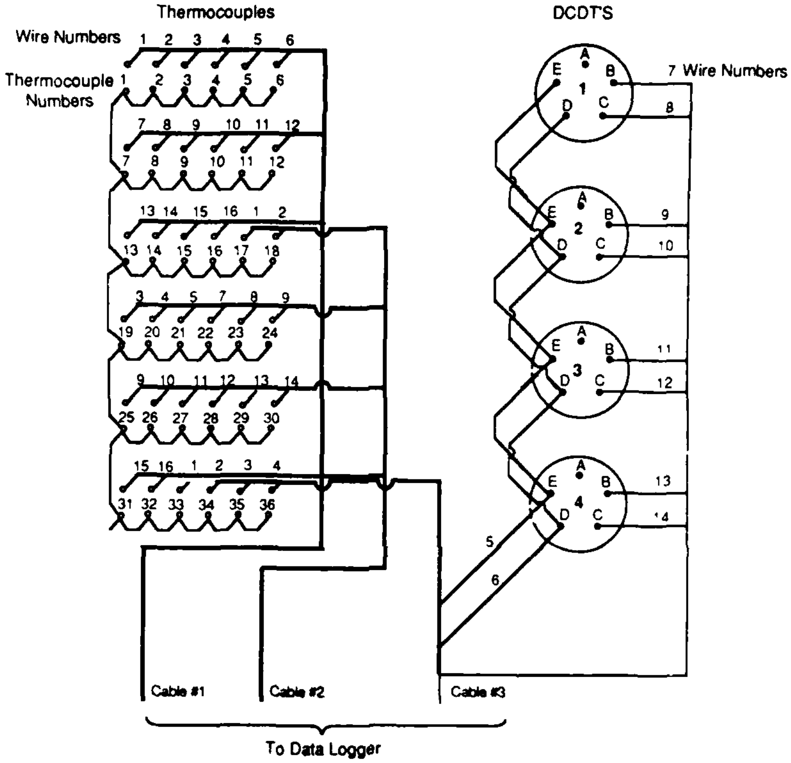
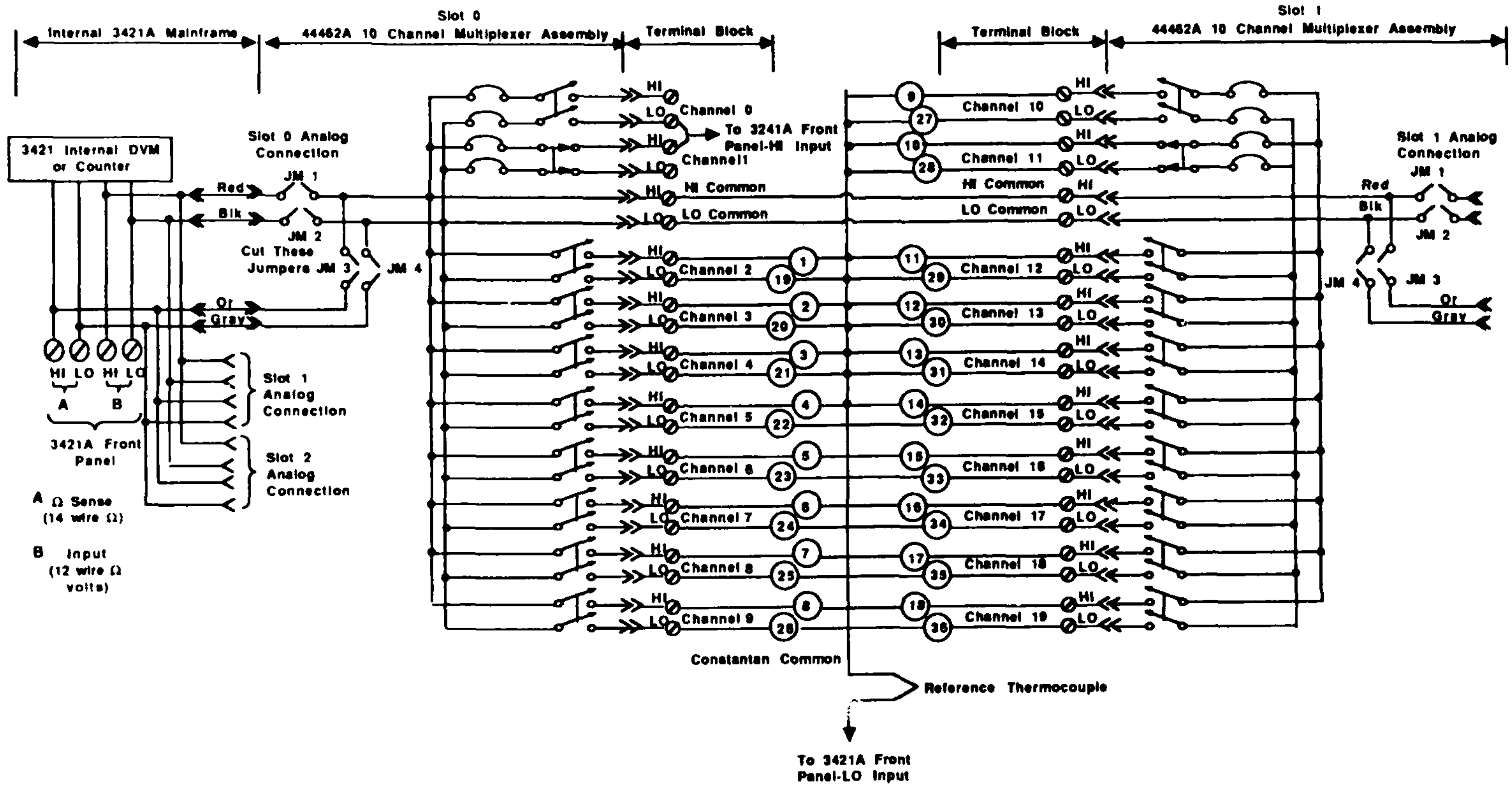


Figure B1. Schematic for wiring of thermocouple junction box.



Wire no.	T/C no.	Wire no.	T/C no.	Wire no.	T/C no.
1	1-1	13	2-5	25	4-1
2	1-2	14	2-6	26	4-2
3	1-3	15	2-7	27	4-3
4	1-4	16	2-8	28	4-4
5	1-5	17	3-1	29	4-5
6	1-6	18	3-2	30	4-6
7	1-7	19	3-3	31	4-7
8	1-8	20	3-4	32	4-8
9	2-1	21	3-5	33	cold bath 1
10	2-2	22	3-6	34	cold bath 2
11	2-3	23	3-7	35	ambient
12	2-4	24	3-8	36	ice bath

Figure B2. Schematic of single-ended thermocouple connections to multiplexer cards 0 and 1 in the HP3421A data logger (after Hewlett-Packard 1982).

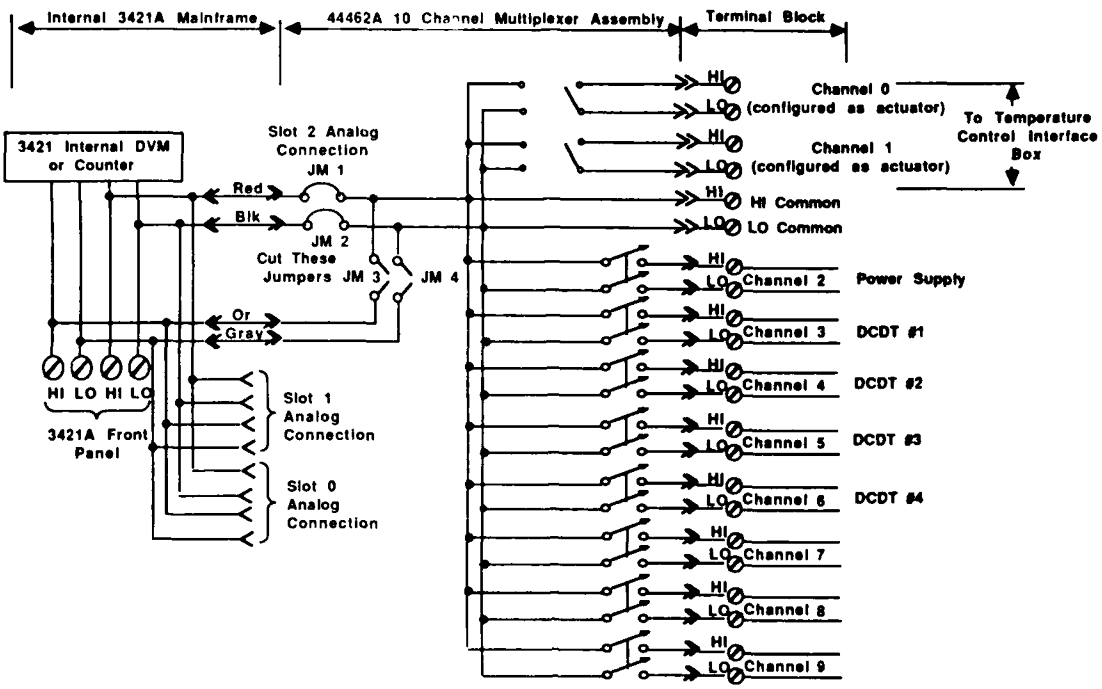
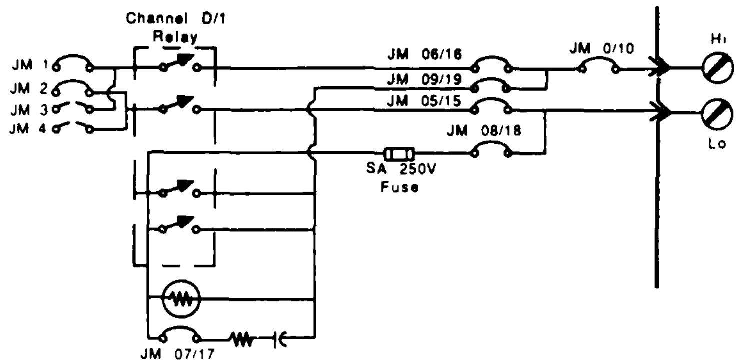


Figure B3. Connections to multiplexer card 2 in the HP3421 data logger (after Hewlett-Packard 1982).

B2. Data logger settings



HP3421 A multiplexer card configuration.

Card	JM06/16* JM05/15	JM09/19* JM08/18	JM1* JM2	J6†	J7†	J8**
0	install	cut	cut	1	1	out
1	install	cut	cut	0	0	out
2	cut	install	install	1	1	out

* Configures channels 0 and 1 as either actuators or multiplexers; locations shown above.

† Tells mainframe how channels 0 and 1 are configured; locations not shown. See manual for further details.

**Bypasses attenuator on channel 2.

Figure B4. HP3421A data logger multiplexer card configurations (after Hewlett-Packard 1982).

B3. Set-up of refrigerated circulating baths

Each bath requires 15-A service. It is recommended that the baths be plugged into different circuits.

a. Rear panel switches:

Remote/local - Local

Programmer/accessory - Off

b. Front panel switches:

PWR - On

Cooling system - On

Setpoint select - Dial

c. Turn dial to desired temperature.

d. Ensure that bath is filled with proper fluid to correct level.

e. Plug in option 1 control box.

f. Connect cables to bath 1 and bath 2 as marked on option 1 box.

g. Connect cable to HP3421A data acquisition system channel 20 and channel 21; red wire to both channel high's, black wire to channel 20 low, white wire to channel 21 low.

h. Energize option 1 control box.

i. Allow system to operate at least 4 hours before attempting any temperature adjustments.

j. Adjust dial and fine tune for desired dial temperature. Allow 5 minutes, after HEAT light begins to flash, between adjustments to ensure system stability.

k. Once dial and fine tune are set, the fine tune knob must not be adjusted again. Note position (setting) of fine tune.

l. Select T_2 and adjust only the T_2 pot for desired temperature. Do not use fine tune. Wait 5 minutes as in step 10. A clockwise adjustment increases bath temperature.

m. Repeat step 12 for T_1 and T_0.

n. Once all setpoints have been adjusted, set local/remote switch on rear panel to remote.

o. Connect HP41CX to HP3421A. Ensure that the remote/local switch is in remote. Verify temperature settings by selecting temperature setpoints with calculator and observing temperature at which they stabilize (see Table B1).

Table B1. Relay settings for temperature control.

Channel 20	Channel 21	Selected setting
0*	0	T_0
0	1	T_2
1	0	Dial
1	1	T_1

*0 = open relay; 1 = closed relay.

APPENDIX C: PROGRAM LISTINGS

C1. Freeze test program

These programs are all stored on the tape cassette marked NEW FREEZE.

NAME	TYPE	REGS
ALMRST	PR	5
ILOG	PR	13
ALMA	PR	27
TAPE	PR	5
PRDATA	PR	101
FRST	PR,A	19
REGRESS	PR	14
REDUCE	PR	47
FRDATA	PR	17
FRPEN	PR	27
DATA	PR	33
SCAN	PR	54
TLOG	PR	18
TBATHS	PR	23
SCANLMP	PR	34
SCANZ	PR	104
ALAMAZ	PR	38
FR	PR,A	11
TCONTRL	PR	76
FREEZE6	WA	336
FREEZE2	WA	336
TEND	PR	65

C2. Program to load setup programs

This program automatically loads programs used in the initial setup of the freeze test. To load:

a. Place NEW FREEZE program tape in cassette drive.

b. Turn on all devices in loop.

c. Press α FR α.

d. XEQ α READP α.

Time required to load FR is 1 minute and 10 seconds.

```
 4:57PM 03.04
01♦LBL "FR"
02 CF 11                    Disables automatic execution flag.
03 1
04 STO 01
05 "PR"
06 ASTO 02
07 "DA"
08 ASTO 03
09♦LBL 04
10 RCL 01                   Clears all data and program files from the
11 EMDIRX                     extended memory (EM).
12 RCL 02
13 X=Y?
14 GTO 01
15 RDN
16 RCL 03
17 X=Y?
18 GTO 01
19 GTO 03
20♦LBL 01
21 PURFL
22 GTO 04
23♦LBL 03
24 "TSAVE2"
25 36                       Creates "TSAVE2" file in EM.
26 CRFLD
27 "TSAVE3"
28 45                       Creates "TSAVE3" file in EM.
29 CRFLD
30 "FREEZE2"
31 READA                    Loads main memory files, set flags and key assign-
32 .END.                      ments and fills registers with proper constants.
```

C3. Setup programs

```
                CAT 1
LBL'ALAMAZ
END        260 BYTES
LBL'SCANLMP
END        237 BYTES
LBL'TBATHS
END        161 BYTES
LBL'TAPE
END        35 BYTES
LBL'SCANZ
.END.      728 BYTES
                CAT 4
TSAVE2  D036
TSAVE3  D045
        515.0000    ***
```

- ALAMAZ - calibrates thermocouple zeros.
- SCANLMP - scans and prints DCDTs.
- TBATHS - scans and prints bath temperatures.
- TAPE - initializes data tape.
- SCANZ - subroutine for ALAMAZ.

```
USER KEYS:
 12 "TAPE"
 13 "TBATHS"
 14 "SCANLMP"
 15 "ALAMAZ"
```

- TAPE is assigned to "1/X" key.
- SCANZ - subroutine for ALAMAZ.
- SCANLMP is assigned to "LOG" key.
- ALAMAZ is assigned to "LN" key.

```
STATUS:
SIZE= 100
Σ= 11
DEG
FIX 4
```

C4. Initial Register storage for the setup programs

```
R00= 0.000000
R01= 0.000000
R02= 0.000000
R03= 0.000000
R04= 0.000000
R05= 0.000000
R06= 0.000000
R07= 0.000000
R08= 0.000000
R09= 0.000000
R10= 0.000000
R11= 0.000000
R12= 0.000000
R13= 0.000000
R14= 0.000000
R15= 0.000000
R16= 0.000000
R17= 0.000000
R18= 0.000000
R19= 0.000000
R20= 0.000000
R21= 0.000000
R22= 0.000000
R23= 0.000000
R24= 0.000000
R25= 0.000000
R26= 0.000000
R27= 0.000000
R28= 0.000000
R29= 0.000000
R30= 0.000000
R31= 0.000000
R32= 0.000000
R33= 0.000000
R34= 0.000000
R35= 0.000000
R36= 0.000000
R37= 0.000000
R38= 0.000000
R39= 0.000000
R40= 0.000000
R41= 0.000000
R42= 0.000000
R43= 0.000000
R44= 0.000000
R45= 0.000000
R46= 0.000000
R47= 0.000000
R48= 0.000000
R49= 0.000000
```

R50=	0.000000	
R51=	0.000000	
R52=	0.000000	
R53=	0.000000	
R54=	0.000000	
R55=	0.000000	
R56=	0.000000	
R57=	0.000000	
R58=	0.000000	
R59=	0.000000	
R60=	0.000000	
R61=	0.000000	
R62=	0.000000	
R63=	0.000000	
R64=	0.000000	
R65=	0.000000	
R66=	0.000000	
R67=	0.000000	
R68=	0.000000	
R69=	0.000000	
R70=	0.000000	
R71=	0.000000	
R72=	0.000000	
R73=	0.000000	
R74=	12.700000	
R75=	38.100000	
R76=	63.500000	
R77=	88.900000	Thermocouple depths in millimetres.
R78=	114.300000	
R79=	139.700000	
R80=	152.400000	
R81=	0.000038	Thermocouple calibrations in V/°C.
R82=	0.000000	
R83=	0.000000	
R84=	0.000000	
R85=	0.000000	
R86=	0.000000	
R87=	0.000000	
R88=	9.498900	DCDT calibration in mm/V for 6 V-dc input.
R89=	0.000000	
R90=	0.000000	
R91=	0.000000	
R92=	0.000000	
R93=	0.000000	
R94=	0.000000	
R95=	0.000000	
R96=	0.000000	
R97=	0.000000	
R98=	0.000000	
R99=	0.000000	

C5. Initial flag status for setup programs

```
FLAGS:
F 00  CLEAR
F 01  CLEAR
F 02  CLEAR
F 03  CLEAR
F 04  CLEAR
F 05  CLEAR
F 06  CLEAR
F 07  CLEAR
F 08  CLEAR
F 09  CLEAR
F 10  CLEAR
F 11  CLEAR
F 12  CLEAR
F 13  CLEAR
F 14  CLEAR
F 15  CLEAR
F 16  CLEAR
F 17  CLEAR
F 18  CLEAR
F 19  CLEAR
F 20  CLEAR
F 21  SET
F 22  SET
F 23  SET
F 24  CLEAR
F 25  CLEAR
F 26  SET
F 27  CLEAR
F 28  SET
F 29  SET
F 30  CLEAR
F 31  SET
F 32  CLEAR
F 33  CLEAR
F 34  CLEAR
F 35  CLEAR
F 36  CLEAR
F 37  SET
F 38  CLEAR
F 39  CLEAR
F 40  SET
F 41  CLEAR
F 42  CLEAR
F 43  CLEAR
F 44  CLEAR
F 45  CLEAR
F 46  CLEAR
F 47  CLEAR
F 48  CLEAR
F 49  CLEAR
F 50  CLEAR
F 51  CLEAR
F 52  CLEAR
F 53  CLEAR
F 54  CLEAR
F 55  SET
```

C6. <u>Program to determine the thermocouple zero calibrations during initial setup</u>

1:24PM 03.04	
01♦LBL "ALAMAZ"	
02 CF 27	Turns off USER.
03 "HP3421A"	
04 FINDID	Makes data logger primary device.
05 SELECT	
06 0	Initializes scan number counter.
07 STO 07	
08 "TSAVE3"	
09 000.	
10 SEEKPTA	Stores depth data in EM file "TSAVE3."
11 073.080	
12 SAVERX	
13 08.04301	
14 STO 95	
15♦LBL 04	
16 0.0	
17 STO IND 95	Places zeros in R08-R43 and in extended memory file "TSAVE2."
18 ISG 95	
19 GTO 04	
20 "TSAVE2"	
21 000.	
22 SEEKPTA	
23 008.043	
24 SAVERX	
25 "SERIES NAME?"	
26 AON	
27 PROMPT	
28 ASTO 00	
29 "SAMP1 NAME?"	
30 PROMPT	
31 ASTO 01	Prompts for series and sample names (limit to 7 alpha-numeric characters).
32 "SAMP2 NAME?"	
33 PROMPT	
34 ASTO 02	
35 "SAMP3 NAME?"	
36 PROMPT	
37 ASTO 03	
38 "SAMP4 NAME?"	
39 PROMPT	
40 ASTO 04	
41 AOFF	
42 "NO. OF SCANS?"	Prompts for number of scans.
43 PROMPT	
44 STO 90	
45 "SCAN INT?"	
46 PROMPT	Prompts for scan interval; defaults to 30 minutes if there is no input.
47 FC?C 22	
48 00.3000	
49♦LBL 00	

```
50 "START DATE"
51 PROMPT
52 FC?C 22
53 DATE
54 STO 05
```

Prompts for start date; defaults to current date.

```
55 "START TIME?"
56 PROMPT
57 FC?C 22
58 TIME
59 .0010
60 HMS+
61 STO 06
```

Prompts for start time; defaults to current time plus 10 seconds.

```
62 "↑↑SCANZ"
63 XYZALM
```

Sets alarm to trigger SCANZ program.

```
64 END
```

C7. <u>Subroutine for ALAMAZ</u>

Program	Comments
1:19PM 03.04	
01♦LBL "SCANZ"	
02 1	Increments counter for scan number.
03 ST+ 07	
04 SF 04	Sets flag to enable low/high side single-ended readings.
05 00	Identifies low side relay 00.
06♦LBL 04	
07 "CLS"	Closes low side relay if preceded by 00, high side if preceded by 01.
08 ARCL X	
09 OUTA	
10 "LS02-19:F1T3"	
11 OUTA	Reads dc-voltage on channels 02-19 and stores data in 3421A buffer.
12 FS? 04	
13 GTO 01	
14 08.02501	Sets up storage of low side readings in R26-R43 and high side readings in R08-R25
15 GTO 02	
16♦LBL 01	
17 26.04301	
18♦LBL 02	
19 STO 95	
20♦LBL 05	
21 IND	Sends dc-voltage data from 3421A buffer to R08-R43 in HP041CX.
22 STO IND 95	
23 ISG 95	
24 GTO 05	
25 FS?C 04	
26 GTO 01	Flag 04 set for low side readings just made; if set, clears flag 04 and changes channel ID to 01 to enable high side readings, and returns to LBL04 to read relays 2-19 again.
27 GTO 03	
28♦LBL 01	
29 "OPN00"	
30 OUTA	
31 01	
32 GTO 04	
33♦LBL 03	
34 "OPN01"	Opens relays 01 and 19.
35 OUTA	
36 "OPN19"	
37 OUTA	
38♦LBL 09	
39 "---------------"	
40 PRA	
41 FIX 2	
42 "TIME= "	
43 ACA	
44 TIME	
45 ACX	
46 PRBUF	Prints time and date heading.
47 CLA	
48 "DATE= "	
49 ACA	
50 FIX 6	
51 DATE	
52 ACX	
53 PRBUF	
54 CLA	
55 FIX 2	
56 "---------------"	
57 PRA	

Program steps	Description
58 CLA 59 PRA 60 SF 12 61 FC? 05 62 GTO 01 63 "AVG TC ZEROS" 64 GTO 00 65♦LBL 01 66 "T/C ZEROS" 67♦LBL 00 68 PRA	Prints "T/C ZERO" reading if flag 12 is clear; prints "AVG T/C ZEROS" if flag 12 is set.
69 CLA 70 PRA 71 ARCL 00 72 PRA	Prints series identification.
73 "TSAVE3" 74 000. 75 SEEKPTA 76 073.080 77 GETRX	Gets depth data from EM.
78 08.03901 79 STO 95	Sets counter for T/Cs.
80 01.00401 81 STO 98	Sets counter for sample IDs.
82♦LBL 08 83 CLA 84 PRA 85 SF 12 86 ARCL IND 98 87 PRA 88 CF 12 89 CLA 90 PRA	Prints sample identification.
91 73.08001 92 STO 99	Sets counter for depths.
93 CLA 94 " DEPTH " 95 ACA 96 " TEMP" 97 ACA 98 ADV 99 "MM " 100 ACA 101 " DEG C" 102 ACA 103 ADV 104 CLA 105 PRA	Prints headings for depth and temperature.
106♦LBL 10 107 RCL IND 99 108 ACX 109 2 110 SKPCHR 111 RCL IND 95 112 RCL 81 113 / 114 STO IND 95 115 ACX 116 ADV	Calculates and prints depth and temperature.

```
ISG 95
GTO 01
♦LBL 01
ISG 99
GTO 10
CLA
PRA
ISG 98
GTO 08
```

```
40.04301
STO 95
```

Sets counter for cold-bath, warm-bath and ice-bath temperatures, and ambient temperature.

```
♦LBL 12
RCL IND 95
RCL 81
/
STO IND 95
ISG 95
GTO 12
FIX 2
CLA
PRA
"COLD BATH= "
ACA
RCL 40
ACX
" DEG C"
ACA
PRBUF
CLA
"WARM BATH= "
ACA
RCL 41
ACX
" DEG C"
ACA
PRBUF
CLA
"AMBIENT= "
ACA
RCL 42
ACX
" DEG C"
ACA
PRBUF
CLA
"ICE BATH= "
ACA
RCL 43
ACX
" DEG C"
ACA
PRBUF
CLA
PRA
"END OF READING"
PRA
```

Calculates and prints cold-bath, warm-bath and ice-bath temperatures, and ambient temperature.

173 FS?C 05 174 GTO 11	If flag 05 is set then six sets of readings have been made.
175 "TSAVE2" 176 000. 177 SEEKPTA 178 044.079 179 GETRX	Gets $\sum$ T/C data from EM.
180 44.07901 181 STO 96	Sets counter for $\sum$ T/C data.
182 08.04301 183 STO 95	Sets counter for T/C data just read.
184♦LBL 13 185 RCL IND 95 186 RCL IND 96 187 + 188 STO IND 96 189 ISG 95 190 GTO 01 191♦LBL 01 192 ISG 96 193 GTO 13	Adds current T/C data to $\sum$ T/C data.
194 "TSAVE2" 195 000. 196 SEEKPTA 197 044.079 198 SAVERX	Stores $\sum$ T/C data in EM.
199 RCL 90 200 RCL 07 201 X<Y? 202 GTO 07	If number of scans equals number of scans desired; proceeds to determining average T/C zeros.
203 044.07901 204 STO 96	Sets counter for $\sum$ T/C data.
205 08.04301 206 STO 95	Sets counter for T/C data just read.
207♦LBL 06 208 RCL IND 96 209 RCL 07 210 / 211 RCL 81 212 * 213 STO IND 95 214 ISG 96 215 GTO 00 216♦LBL 00 217 ISG 95 218 GTO 06 219 CLRALMS 220 SF 05 221 GTO 09	Calculates average T/C zeros, clears the alarms, sets flag 05 to enable printing "AVG. T/C ZERO" heading, and returns to section for printing headings, and depth and temperature data.
222♦LBL 11 223 "TSAVE2" 224 000. 225 SEEKPTA 226 08.043 227 SAVERX	Saves "AVG T/C ZERO" data in EM.

```
228♦LBL 07
229 "TSAVE3"
230 000.
231 SEEKPTA
232 073.080
233 GETRX
234 PWRDN
235 OFF
236 END
```

Returns depth data from EM to R73-R80.

C8. Program to make readings of the displacement transducers during setup

1:26PM 03.04 01♦LBL "SCANLMP"	
02 CF 27	• Clears USER.
03 "HP3421A" 04 FINDID 05 SELECT	Makes data logger primary device.
06 "LS22-26:F1T3" 07 OUTA 08 44.04801 09 STO 95 10♦LBL 06 11 IND 12 STO IND 95 13 ISG 95 14 GTO 06	Reads dc-voltage data on channels 22-26 and stores values in R44-R48 in HP41CX.
15 "OPN26" 16 OUTA	Opens channel 26.
17 45.04801 18 STO 95	Sets counter for voltage data from DCDTs.
19♦LBL 14 20 RCL IND 95 21 RCL 88 22 * 23 RCL 44 24 * 25 6 26 / 27 STO IND 95 28 ISG 95 29 GTO 14	Converts dc-voltage data to displacement in millimetres.
30 FIX 1 31 CLA 32 PRA 33 "DCTD1= " 34 ACA 35 RCL 45 36 ACX 37 " MM." 38 ACA 39 PRBUF 40 CLA 41 "DCDT2= " 42 ACA 43 RCL 46 44 ACX 45 " MM." 46 ACA 47 PRBUF 48 CLA 49 "DCDT3= " 50 ACA 51 RCL 47 52 ACX 53 " MM." 54 ACA 55 PRBUF	Prints the DCDT readings in millimetres.

```
56 CLA
57 "DCDT4= "
58 ACA
59 RCL 48
60 ACX
61 " MM."
62 ACA
63 PRBUF
64 CLA
65 FIX 4
66 "PWR IN= "
67 ACA
68 RCL 44
69 ACX
70 " DCV"
71 ACA
72 PRBUF
73 CLA
74 PRA
75 "END OF READING"
76 END
```

Continuation of displacement DCDT printout.

C9. Program to scan the bath temperatures during setup

```
 1:29PM 03.04
01♦LBL "TBATHS"
02 PWRUP                 •  Powers up devices.
03 CF 27                 •  Clears USER.
04 "TSAVE2"
05 032.                     Gets T/C zero data for bath temperatures from EM
06 SEEKPTA                    and stores in R98 and R99.
07 098.099
08 GETRX
09 "CLS00"
10 OUTA
11 "LS16-17:F1T3"
12 OUTA
13 08.00901
14 STO 95                   Reads channels 16 and 17 and stores data in R08
15♦LBL 01                     and R09.
16 IND
17 STO IND 95
18 ISG 95
19 GTO 01
20 CLA
21 "COLD BATH= "
22 ACA
23 RCL 08
24 RCL 81
25 /                        Calculates and prints cold-bath temperature in °C.
26 RCL 98
27 -
28 ACX
29 " DEG C"
30 PRBUF
31 CLA
32 "WARM BATH= "
33 ACA
34 RCL 09
35 RCL 81
36 /
37 RCL 99                   Calculates and prints warm-bath temperature in °C.
38 -
39 ACX
40 " DEG C"
41 PRBUF
42 CLA
43 PRA
44 "OPN17"
45 OUTA                     Opens last channel opened on data logger.
46 PWRDN                 •  Powers down devices.
47 OFF                   •  Turns off HP41CX.
48 END
```

C10. Program to initialize the data tape cassette during setup

Tape must be first initialized to contain 1 file by:
XEQ "NEWM 0 0 1," which is assigned to 1/X.

```
 1:33PM 03.04
01♦LBL "TAPE"
02 SF 20            Tape enable on.
03 CLA              Places series name in alpha register.
04 ARCL 00
05 16000            Sets up 16,000 registers on tape.
06 CREATE
07 0
08 STO 89           Sets pointer to zero and stores 0 in R89.
09 SEEKR
10 RTN
11 .END.
```

C11. Program to load running programs

This program automatically loads system running programs for the freezing test. To load:

a. Place NEWFREEZE program tape in cassette drive.

b. Turn on all devices in loop.

c. Press αFRSTα and XEQαREADPα.

The time required to load is 3 minutes, 20 seconds. Automatic execution flag (F11) is set automatically when program FRST is read from cassette.

```
 4:59PM 03.04
01•LBL "FRST"
02 CF 11            •  Disables automatic execution flag.
03 "TSAVE4"
04 16                  Creates "TSAVE4" file in EM.
05 CRFLD
06 "TSAVE5"
07 2                   Creates "TSAVE5" file in EM.
08 CRFLD
09 "TCONTRL"
10 READSUB
11 SAVEP
12 "DATA"
13 READP
14 SAVEP
15 "FRPEN"
16 READP
17 SAVEP
18 "FRDATA"
19 READP
20 SAVEP               Loads EM files.
21 "REDUCE"
22 READP
23 SAVEP
24 "REGRESS"
25 READP
26 SAVEP
27 "PRDATA"
28 READP
29 SAVEP
30 "TEND"
31 READP
32 SAVEP
33 "FREEZE6"           Loads main memory (MM) files and key assignments,
34 READA                 sets flags, and places constants in storage
35 .END.                 registers.
```

C12. Running programs

```
FRST
                    CAT 1
LBL'ILOG
END         31 BYTES
LBL'TLOG
END         126 BYTES
LBL'ALMA
END         189 BYTES
LBL'SCAN
END         370 BYTES
LBL'TCONTRL
LBL'AL1
LBL'AL2
LBL'AL3
LBL'AL4
LBL'AL5
LBL'AL6
LBL'AL7
LBL'AL8
LBL'AL9
LBL'AL10
LBL'ALMRST
LBL'ALMREL
.END.       544 BYTES
```

Main memory files.

```
                    CAT 4
TSAVE2  D036
TSAVE3  D045
TSAVE4  D016
TSAVE5  D002
TCONTRL P077
DATA    P034
FRPEN   P028
FRDATA  P018
REDUCE  P048
REGRESS P015
PRDATA  P102
TEND    P066
             89.0    ***
```

Extended memory files.

```
USER KEYS:
 13 "ILOG"   √x
 15 "TLOG"   LN
```

Programs assigned to keys.

```
STATUS:
SIZE= 100
Σ= 11
DEG
FIX 1
```

Initial calculator status.

C13. Running program register storage

R00=	0.0000	R50=	0.0000	
R01=	0.0000	R51=	0.0000	
R02=	0.0000	R52=	0.0000	
R03=	0.0000	R53=	0.0000	
R04=	0.0000	R54=	0.0000	
R05=	0.0000	R55=	0.0000	
R06=	0.0000	R56=	0.0000	
R07=	0.0000	R57=	0.0000	
R08=	0.0000	R58=	0.0000	
R09=	0.0000	R59=	0.0000	
R10=	0.0000	R60=	0.0000	
R11=	0.0000	R61=	0.0000	
R12=	0.0000	R62=	0.0000	
R13=	0.0000	R63=	0.0000	
R14=	0.0000	R64=	0.0000	
R15=	0.0000	R65=	0.0000	
R16=	0.0000	R66=	0.0000	
R17=	0.0000	R67=	0.0000	
R18=	0.0000	R68=	0.0000	
R19=	0.0000	R69=	0.0000	
R20=	0.0000	R70=	0.0000	
R21=	0.0000	R71=	0.0000	
R22=	0.0000	R72=	0.0000	
R23=	0.0000	R73=	0.0000	
R24=	0.0000	R74=	12.7000	
R25=	0.0000	R75=	38.1000	
R26=	0.0000	R76=	63.5000	Thermocouple depths in millimetres.
R27=	0.0000	R77=	88.9000	
R28=	0.0000	R78=	114.3000	
R29=	0.0000	R79=	139.7000	
R30=	0.0000	R80=	152.4000	
R31=	0.0000	R81=	3.8000-05	T/C calibration in V-dc/°C.
R32=	0.0000	R82=	0.0000	
R33=	0.0000	R83=	0.0000	
R34=	0.0000	R84=	0.0000	
R35=	0.0000	R85=	0.0000	
R36=	0.0000	R86=	0.0000	
R37=	0.0000	R87=	0.0000	
R38=	0.0000	R88=	9.4989	DCTC calibration in millimetres.
R39=	0.0000	R89=	0.0000	
R40=	0.0000	R90=	0.0000	
R41=	0.0000	R91=	0.0000	
R42=	0.0000	R92=	0.0000	
R43=	0.0000	R93=	0.0000	
R44=	0.0000	R94=	0.0000	
R45=	0.0000	R95=	0.0000	
R46=	0.0000	R96=	0.0000	
R47=	0.0000	R97=	0.0000	
R48=	0.0000	R98=	0.0000	
R49=	0.0000	R99=	0.0000	

C14. <u>Flag settings</u>

FLAGS:

F 00	CLEAR	
F 01	CLEAR	
F 02	CLEAR	
F 03	CLEAR	
F 04	CLEAR	All user delegated flags are clear.
F 05	CLEAR	
F 06	CLEAR	
F 07	CLEAR	
F 08	CLEAR	
F 09	CLEAR	
F 10	CLEAR	
F 11	CLEAR	Automatic execution flag is clear.
F 12	CLEAR	
F 13	CLEAR	
F 14	CLEAR	
F 15	CLEAR	All external device control flags are clear.
F 16	CLEAR	
F 17	CLEAR	
F 18	CLEAR	
F 19	CLEAR	
F 20	CLEAR	
F 21	SET	
F 22	CLEAR	
F 23	CLEAR	
F 24	CLEAR	
F 25	CLEAR	
F 26	SET	
F 27	CLEAR	
F 28	SET	
F 29	SET	
F 30	CLEAR	
F 31	SET	
F 32	CLEAR	
F 33	CLEAR	
F 34	CLEAR	
F 35	CLEAR	
F 36	CLEAR	
F 37	CLEAR	
F 38	CLEAR	
F 39	SET	
F 40	SET	System operation control flags (see HP-41CX owner's manual for details).
F 41	CLEAR	
F 42	CLEAR	
F 43	CLEAR	
F 44	CLEAR	
F 45	CLEAR	
F 46	CLEAR	
F 47	CLEAR	
F 48	CLEAR	
F 49	CLEAR	
F 50	CLEAR	
F 51	CLEAR	
F 52	CLEAR	
F 53	CLEAR	
F 54	CLEAR	
F 55	SET	

C15. ILOG

This program allows data readings to be made between regular scan intervals. A SCAN will not be allowed if a scheduled reading is to occur within 8 minutes. The program is assigned to √X key; press USER, then √X key to execute ILOG.

```
 3:42PM 04.05
01*LBL "ILOG"
02 CF 27                    Clears USER key.
03 SF 25
04 1
05 RCLALM                   Recalls first alarm parameters; if no alarm is
06 FC? 25                     set, goes to SCAN.
07 GTO 02
08 CF 25
09 TIME
10 HMS-
11 HR                       If time left before next alarm is less than 8
12 .1333                      minutes (0.1333 hour) then will not scan.
13 X>Y?
14 GTO 01
15*LBL 02
16 "HP3421A"
17 FINDID                   Makes data logger primary device.
18 SELECT
19 XEQ "SCAN"               Executes SCAN program.
20*LBL 01
21 "WAIT FOR SCHED"
22 "FAILED SCAN"            Prints message if SCAN is not allowed.
23 PRA
24 AVIEW
25 END
```

C16. TLOG

This program ensures that zeros are placed in certain storage registers and data files. Data logger is made primary device in HPIL loop. It executes alarm progrm to start readings.

4:29PM 04/18	
01♦LBL "TLOG"	
02 SF 09	• Sets flag to identify first scan.
03 CF 27	• Turns off USER key.
04 000.072	
05 CLRGX	
06 082.087	Puts zeros in R00-R72, R82-R87 and R90-R99.
07 CLRGX	
08 089.099	
09 CLRGX	
10 "TSAVE3"	
11 000.	Puts zeros in file "TSAVE3" in the EM of HP41CX.
12 SEEKPTA	
13 000.044	
14 SAVERX	
15 "TSAVE4"	
16 000.	
17 SEEKPTA	Puts zeros in "TSAVE4" in EM.
18 000.015	
19 SAVERX	
20 "TSAVE5"	
21 000.	
22 SEEKPTA	Puts zeros in "TSAVE5" in EM.
23 000.001	
24 SAVERX	
25 "HP3421A"	
26 FINDID	Finds and makes the HP3421A data logger the primary device.
27 SELECT	
28 XEQ "ALMA"	• Executes "ALMA" program.
29 END	

C17. ALMA

This program provides prompts for test information and executes setting of alarms.

2:35PM 04/02	
01♦LBL "ALMA"	
02 "SERIES NAME?"	
03 AON	Prompts for series name and stores in R00.
04 PROMPT	
05 ASTO 00	
06 "SAMP1 NAME?"	
07 PROMPT	
08 ASTO 01	
09 "SAMP2 NAME?"	
10 PROMPT	
11 ASTO 02	Prompts for sample names and stores in R01-R04.
12 "SAMP3 NAME?"	
13 PROMPT	
14 ASTO 03	
15 "SAMP4 NAME?"	
16 PROMPT	
17 ASTO 04	
18 AOFF	
19 "FREEZE TEMP?"	
20 PROMPT	Prompts for freezing point depression and stores
21 STO 94	in R94.
22 CF 22	
23 "START DATE?"	
24 PROMPT	Prompts for start date; defaults to current date
25 FC?C 22	if only R/S is pushed.
26 DATE	
27 "START TIME?"	
28 PROMPT	
29 FC?C 22	
30 TIME	
31 .01	
32 HMS+	Prompts for start time; defaults to current time
33 ENTER↑	plus 1 minute if only R/S is keyed.
34 24	
35 /	Stores start date in R82.
36 ENTER↑	
37 RDN	Stores start time in R83.
38 INT	
39 DATE+	
40 STO 82	
41 RCL Z	
42 FRC	
43 24	
44 *	
45 STO 83	
46 XEQ "TCONTRL"	Executes TCONTRL alarm setting program
47 2	
48 RCL 82	
49 RCL 83	Sets SCAN alarm to 2 hour intervals.
50 "↑↑SCAN"	
51 XYZALM	
52 END	

C18. SCAN

1:50PM 30.04 01♦LBL "SCAN"	
02 CF 27	• Clears USER.
03 SF 04	• Sets flag for low side readings.
04 DATE 05 STO 05 06 TIME 07 STO 06	Places date and time of readings in R05 and R06.
08 00 09♦LBL 12 10 "CLS" 11 ARCL X 12 OUTA	Closes low side relay if preceded by 00 and high side relay if 01.
13 "LS02-19:F1T3" 14 OUTA	Reads dc-voltage stepwise on channels 2-19 and stores results in 3421A buffer.
15 FS? 04 16 GTO 00 17 08.02501 18 GTO 01 19♦LBL 00 20 26.04301 21♦LBL 01 22 STO 95	Sets up storage of low side readings in R26-R43 and high side readings in R08-R25.
23♦LBL 04 24 IND 25 STO IND 95 26 ISG 95 27 GTO 04 28 FS?C 04	Sends dc-voltage data from buffer to R08-R43 in HP41CX.
29 GTO 03 30 GTO 02 31♦LBL 03 32 "OPN00" 33 OUTA 34 01 35 GTO 12 36♦LBL 02 37 "OPN01" 38 OUTA	Flag 04 is set if low side readings just made; if set, enables channel ID change to 01 to enable high side readings and returns to LBL 12 to read relays 2-19 again. If flag 04 is cleared, proceeds to read channels 22-26, opens relays 00 and 01 before reading 22-26.
39 "LS22-26:F1T3" 40 OUTA	Reads dc-voltage stepwise on channels 22-26, stores in buffer.
41 44.04801 42 STO 95 43♦LBL 08 44 IND 45 STO IND 95 46 ISG 95 47 GTO 08	Sends dc-voltage data from buffer to R44-R48.
48 "OPN26" 49 OUTA	Opens last channel relay.

```
"DATA"
GETP
XEQ "DATA"
```

Gets "DATA" program from EM and reduces dc-voltage data to °C and mm.

```
"FRPEN"
GETP
XEQ "FRPEN"
```

Gets "FRPEN" program from EM and calculates the frost penetrations.

```
"REDUCE"
GETP
"FRDATA"
GETSUB
"REGRESS"
GETSUB
XEQ "REDUCE"
```

Gets "REDUCE," "FRDATA" and "REGRESS" programs from EM and determines: 1) frost heave rate, 2) frost penetration, 3) frost penetration rate, 4) heave ratio, and 5) segregation potential.

```
"REDUCE"
PCLPS
"PRDATA"
GETP
XEQ "PRDATA"
```

Gets "PRDATA" program from EM and prints out test results.

```
01.072
STO 99
CLA
ARCL 00
RCL 89
SEEKR
RCL 99
WRTRX
72
ST+ 89
```

Writes data on tape cassette.

```
"TSAVE4"
000.
SEEKPTA
049.064
GETRX
```

Returns data from EM to main memory (MM).

```
"TCONTRL"
GETP
```

Resets HP41CX MM to initial condition.

```
049.053004
REGMOVE
045.049004
REGMOVE
061.065004
REGMOVE
057.061004
REGMOVE
```

Shifts past two sets of frost heave and frost penetration readings to new storage for rate calculations.

```
CF 10
RCL 07
120.5
X>Y?
GTO 01
"TEND"
GETP
GTO "TEND"
```

Enables termination of test if the elapsed time is greater than 120.5 hours.

```
•LBL 01
PWRDN
```

• Turns off devices.

```
OFF
END
```

• Turns off HP41CX.

C19. Program to control bath temperatures during the freeze-thaw test

```
10:51AM 05.05
01♦LBL "TCONTRL"
02 SF 08
```

Prevents printing of dh/dt, etc., in PRDATA.

```
03 0
04 "↑↑AL1"
05 GTO "ALMREL"
06♦LBL "AL1"
07 "OPN20"
08 XEQ "OUTA"
09 "CLS21"
10 XEQ "OUTA"
```

Sets alarm at tn_0 + 6 minutes for setting bath temperatures at T_1 = 12°C and T_2 = 3°C, and triggers alarm.

```
11 16
12 "↑↑AL2"
13 GTO "ALMREL"
14♦LBL "AL2"
15 "OPN21"
16 XEQ "OUTA"
```

Sets bath temperatures at t_0 + 6 minutes + 16 hours to T_1 = 3°C and T_2 = 3°C.

```
17 24
18 "↑↑AL3"
19 GTO "ALMREL"
20♦LBL "AL3"
21 "CLS20"
22 XEQ "OUTA"
```

Sets bath temperatures at t_0 + 6 minutes + 24 hours to T_1 = -3°C and T_2 = 3°C.

```
23 CF 08
```

Enables printing of dh/dt, etc., in PRDATA, resets scan interval to 30 minutes.

```
24 .3
25 STO 99
26 XEQ "ALMRST"
```

Resets scan interval to 30 minutes.

```
27 32
28 "↑↑AL4"
29 GTO "ALMREL"
30♦LBL "AL4"
31 "CLS21"
32 XEQ "OUTA"
```

Sets bath temperatures at t_0 + 6 minutes + 32 hours to T_1 = -12°C and T_2 = 0.5°C.

```
33 48
34 "↑↑AL5"
35 GTO "ALMREL"
36♦LBL "AL5"
37 "OPN20"
38 XEQ "OUTA"
```

Sets bath temperatures at t_0 + 6 minutes + 48 hours to T_1 = 12°C and T_2 = 3°C.

```
39 SF 08
```

Disables printing of dh/dt, etc.

```
40 2.0
41 STO 99
42 XEQ "ALMRST"
```

Resets scan interval to 2 hours.

```
43 64
44 "↑↑AL6"
45 GTO "ALMREL"
46♦LBL "AL6"
47 "OPN21"
48 XEQ "OUTA"
```

Sets bath temperatures at t_0 + 6 minutes + 64 hours to T_1 = 3°C and T_2 = 3°C.

```
49 72
50 "↑↑AL7"
51 GTO "ALMREL"
```

52♦LBL "AL7" 53 "CLS20" 54 XEQ "OUTA"	Sets bath temperatures at t_0 + 6 minutes + 72 hours to T_1 = −3°C and T_2 = 3°C.
55 CF 08	Enables printing of dh/dt, etc.
56 .3 57 STO 99 58 XEQ "ALMRST"	Resets scan interval to 30 minutes.
59 80 60 "↑↑AL8" 61 GTO "ALMREL" 62♦LBL "AL8" 63 "CLS21" 64 XEQ "OUTA"	Sets bath temperatures at t_0 + 6 minutes + 80 hours to T_1 = −12°C and T_2 = −0.5°C.
65 96 66 "↑↑AL9" 67 GTO "ALMREL" 68♦LBL "AL9" 69 "OPN20" 70 XEQ "OUTA"	Sets bath temperatures at t_0 + 6 minutes + 96 hours to T_1 = 12°C and T_2 = 3°C.
71 SF 08	Disables printing of dh/dt, etc.
72 2.0 73 STO 99 74 XEQ "ALMRST"	Rests scan interval to 2 hours.
75 112 76 "↑↑AL10" 77 GTO "ALMREL" 78♦LBL "AL10" 79 "OPN21" 80 XEQ "OUTA"	Sets bath temperatures at t_0 + 6 minutes + 112 hours to T_1 = 3°C *and* T_2 = 3°C.
81 GTO 09	Goes to end of program.
82♦LBL "ALMRST" 83 1 84 XEQ "RCLALM" 85 X<> Z 86 RDN 87 RCL 99 88 X<> Z 89 "↑↑SCAN" 90 XEQ "CLALMA" 91 XYZALM 92 RTN	Subroutine to reset scan interval.

```
 93♦LBL "ALMREL"
 94 RCL 03
 95 HMS+
 96 .06
 97 HMS+
 98 ENTER↑
 99 ENTER↑
100 24
101 /
102 INT
103 RCL 02
104 X<>Y
105 DATE+
106 LASTX
107 24
108 *
109 ST- Z
110 CLX
111 STO T
112 RDN
113 X<>Y
114 XYZALM
115♦LBL 09
116 PWRDN
117 OFF
118 .END.
```

Steps 93–114: Subroutine to set alarms for temperature changes.

- 116 PWRDN: Turns off devices.
- 117 OFF: Turns off HP41CX.

C20. <u>Program to reduce the thermocouple data and the DCDT data during the freeze-thaw test</u>

```
11:37AM 04/03
01♦LBL "DATA"
02 RCL 80
03 RCL 05
04 DDAYS
05 24
06 *
07 RCL 06
08 RCL 83
09 HMS-
10 HMS+
11 HR
12 STO 07
13 "TSAVE3"
14 000.
15 SEEKPTA
16 045.080
17 SAVERX
18 "TSAVE2"
19 000.
20 SEEKPTA
21 045.080
22 GETRX
23 45.08001
24 STO 92
25 08.04301
26 STO 95
27♦LBL 05
28 RCL IND 95
29 RCL 81
30 /
31 RCL IND 92
32 -
33 STO IND 95
34 ISG 95
35 GTO 00
36♦LBL 00
37 ISG 92
38 GTO 05
39♦LBL 00
40 "TSAVE3"
41 000.
42 SEEKPTA
43 045.080
44 GETRX
45 FS?C 09
46 GTO 02
47 GTO 03
```

Steps 02–10: Calculates elapsed time in hours:

R80	start date
R05	current date
R06	current time
R83	start time
R07	elapsed time.

Steps 11–17: Saves data in R45-R80 in EM.

Steps 18–22: Gets T/C zero data from EM; stores in R45-R80.

Steps 23–24: Sets T/C zero counter.

Steps 25–26: Sets T/C temperature counter.

Steps 27–39: Converts dc-voltage data for T/Cs to 0°C and corrects for zero shift:

$$°C = V\text{-dc}/3.8 \times 10^{-5}\ V\text{-dc}/°C$$

$$R81 \leftarrow 3.8 \times 10^{-5}.$$

Steps 40–44: Returns data from EM to R45-R80 in MM.

Steps 45–47: Determines if first data pass (FS09) is made and enables determination of initial DCDT data.

```
48♦LBL 02
49 45.04801
50 STO 96
51 84.08701
52 STO 99
53♦LBL 04
54 RCL IND 96
55 RCL 44
56 *
57 6
58 /
59 STO IND 99
60 ISG 96
61 GTO 00
62♦LBL 00
63 ISG 99
64 GTO 04
65♦LBL 03
```

Determines initial DCDT settings, corrects for input voltage drift from 6.0 V and stores results in R84-R87.

```
66 45.04801
67 STO 96
```

Sets frost heave counter.

```
68 84.08701
69 STO 99
```

Sets $DCDT_{zero}$ counter.

```
70♦LBL 06
71 RCL IND 96
72 RCL 44
73 *
74 6
75 /
76 RCL IND 99
77 -
78 RCL 88
79 *
80 STO IND 96
81 ISG 96
82 GTO 00
83♦LBL 00
84 ISG 99
85 GTO 06
```

Calculates the frost heave for each sample and stores results in R45-R48.

```
86 RTN
87 END
```

Returns to SCAN.

C21. Program to determine the depth of frost penetration during the freeze-thaw test

```
3:26PM 04/18
♦LBL "FRPEN"
```

```
08.03908
STO 99
```

Sets T/C temperature counter by 08.

```
69.07201
STO 93
```

Sets gradT counter.

```
45.04801
STO 96
```

Sets frost heave counter.

```
57.06001
STO 97
```

Sets frost penetration counter.

```
♦LBL 12
RCL 99
.00007
-
STO 95
```

Sets T/C temperature counter by 01.

```
73.07901
STO 90
```

Sets depth counter.

```
♦LBL 04
RCL 95
1
+
STO 92
RCL IND 95
RCL 94
-
SIGN
RCL IND 92
RCL 94
-
SIGN
X≠Y?
GTO 00
ISG 95
GTO 03
♦LBL 03
ISG 90
GTO 04
```

Looks for depth interval where freezing occurs; exits to determine actual frost depth when interval is found.

```
RCL IND 95
RCL 94
-
SIGN
X>0?
GTO 01
```

Checks to see if sample is completely frozen or thawed.

```
RCL IND 96
152.4
+
STO IND 97
GTO 02
```

If completely frozen, sets frost penetration to 152.4 mm.

```
♦LBL 01
0
STO IND 97
```

If completely thawed, sets frost penetration to 0 mm.

```
GTO 02
```

```
52♦LBL 00
53 RCL 90
54 1
55 +
56 STO 91
57 RCL IND 91
58 RCL IND 90
59 -
60 RCL IND 92
61 RCL IND 95          Uses linear interpolation to determine frost depth.
62 -
63 /
64 1/X
65 STO IND 93
66 RCL 94
67 RCL IND 95
68 -
69 X<>Y
70 /
71 RCL IND 90
72 +
73 STO IND 97
74♦LBL 02              Increments T/C counter.
75 ISG 99
76 GTO 02
77♦LBL 02
78 ISG 97               Increments frost penetration counter.
79 GTO 02
80♦LBL 02
81 ISG 93               Increments gradT counter.
82 GTO 02
83♦LBL 02              Increments frost heave counter.
84 ISG 96
85 GTO 12
86 RTN                  Returns to SCAN.
87 .END.
```

C22. <u>Program to determine the frost heave and frost penetration rates, frost heave ratio, and segregation potential</u>

Program	Description
3:29PM 04/18	
♦LBL "REDUCE"	
CLA	Clears alpha register.
RCL 07	Stores $\sum$ time in R90.
STO 90	
"TSAVE5"	
000.	Gets previous two times from "TSAVE5" in EM and stores in R91 and R92.
SEEKPTA	
091.092	
GETRX	
"TSAVE3"	
000.	Stores data in R00-R44 in EM ("TSAVE3").
SEEKPTA	
000.044	
SAVERX	
45.04801	Sets counters:
STO 96	h_1
49.05201	
STO 20	h_2
53.05601	
STO 21	h_3
57.06001	
STO 97	H_1
61.06401	
STO 22	H_2
65.06801	
STO 23	H_3
69.07201	
STO 93	SP_o and gradT
00.00301	
STO 12	dh/dH
04.00701	
STO 13	dh/dt
08.01101	
STO 14	dH/dt
♦LBL 04	
XEQ "FRDATA"	Executes program to calculate $gradT/\frac{dh}{dH}/\frac{dh}{dt}/\frac{dH}{dt}$.
ISG 96	
GTO 00	
♦LBL 00	
ISG 20	
GTO 00	
♦LBL 00	
ISG 21	
GTO 00	Increments counters.
♦LBL 00	
ISG 97	
GTO 00	
♦LBL 00	
ISG 22	
GTO 00	
♦LBL 00	
ISG 23	
GTO 00	
♦LBL 00	

```
55 ISG 93
56 GTO 00
57◆LBL 00
58 ISG 12
59 GTO 00
60◆LBL 00
61 ISG 13
62 GTO 00
63◆LBL 00
64 ISG 14
65 GTO 04
```

Increments counters.

```
66◆LBL 00
67 "TSAVE4"
68 000.
69 SEEKPTA
70 049.064
71 SAVERX
```

Saves data in R49-R64 in EM (TSAVE4).

```
72 000.049004
73 REGMOVE
74 004.053004
75 REGMOVE
76 008.061004
77 REGMOVE
```

Moves $\frac{dh}{dH}, \frac{dh}{dt}, \frac{dH}{dt}$ to new storage in MM.

```
78 "TSAVE3"
79 000.
80 SEEKPTA
81 000.044
82 GETRX
```

Returns T/C temperature data to MM from EM.

```
83 RCL 91
84 STO 92
85 RCL 90
86 STO 91
87 "TSAVE5"
88 000.
89 SEEKPTA
90 091.092
91 SAVERX
```

Places first two time readings into second two storage registers R91 and R92, and stores in EM (TSAVE5).

```
92 RTN
93 .END.
```

Returns to SCAN.

C23. <u>Subroutine to determine heave and penetration rates, frost heave ratio, and segregation potential</u>

```
3:32PM 04/18
01•LBL "FRDATA"
02 RCL IND 96          Places current heave value in R30.
03 STO 30
04 RCL IND 20
05 STO 31              Places previous two heave values in R31 and R32.
06 RCL IND 21
07 STO 32
08 XEQ "REGRESS"       Calculates heave rate in mm/hr.
09 RCL 25
10 24                  Converts to mm/day.
11 *
12 STO 26
13 STO IND 13
14 RCL IND 97          Places current penetration value in R30.
15 STO 30
16 RCL IND 22
17 STO 31              Places previous two heave values in R31 and R32.
18 RCL IND 23
19 STO 32
20 XEQ "REGRESS"       Calculates frost penetration rate in mm/hr.
21 RCL 25
22 24
23 *                   Converts to mm/day.
24 STO 25
25 STO IND 14
26 RCL 26
27 RCL 25
28 X=0?
29 GTO 00
30 RCL 26              Calculates dh/dH.
31 RCL 25
32 /
33 GTO 01
34•LBL 00
35 0
36•LBL 01
37 STO IND 12
38 RCL IND 93
39 X=0?
40 GTO 00
41 RCL 26
42 4.2694
43 *                   Calculates segregation potential.
44 RCL IND 93
45 /
46 GTO 01
47•LBL 00
48 0
49•LBL 01
50 STO IND 93
51 RTN                 Returns to "REDUCE."
52 .END.
```

C24. <u>Program to determine heave rates and penetration rates by regression analysis</u>

```
3:33PM 04/18
01+LBL "REGRESS"
02 RCL 30
03 RCL 90
04 *
05 RCL 31
06 RCL 91
07 *
08 +
09 RCL 32
10 RCL 92
11 *
12 +
13 STO 40
```

$\sum xy$

```
14 RCL 30
15 RCL 31
16 +
17 RCL 32
18 +
19 STO 41
```

$\sum y$ (heave or penetration)

```
20 RCL 90
21 RCL 91
22 +
23 RCL 92
24 +
25 STO 42
```

$\sum x$ (time)

```
26 RCL 90
27 X↑2
28 RCL 91
29 X↑2
30 +
31 RCL 92
32 X↑2
33 +
34 STO 43
```

$\sum x^2$

```
35 RCL 40
36 RCL 41
37 RCL 42
38 *
39 3
40 /
41 -
42 RCL 43
43 RCL 42
44 X↑2
45 3
46 /
47 -
48 /
49 STO 25
```

$$\frac{dh}{dt} \text{ or } \frac{dH}{dt} = \frac{\sum xy - \frac{\sum x \sum y}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}$$

```
50 RTN
51 .END.
```

Returns to FRDATA.

C25. <u>Program to print test results and to store results on a tape cassette</u>

```
10:17AM 04/19
01♦LBL "PRDATA"
02 "..............."
03 PRA
04 FIX 2
05 "TIME: "
06 ACA
07 RCL 06
08 ACX
09 PRBUF
10 CLA
11 "DATE: "
12 ACA
13 FIX 6
14 RCL 05
15 ACX
16 PRBUF
17 CLA
18 FIX 4
19 "Σ TIME: "
20 ACA
21 RCL 07
22 ACX
23 " HOURS"
24 ACA
25 PRBUF
26 CLA
27 "..............."
28 PRA
29 CLA
30 PRA
```

Prints main heading.

```
31 SF 12
32 ARCL 00
33 PRA
```

Prints series ID.

```
34 08.03901
35 STO 95
36 45.04801
37 STO 96
38 01.00401
39 STO 98
40 49.05201
41 STO 90
42 53.05601
43 STO 91
44 57.06001
45 STO 97
46 61.06401
47 STO 92
48 69.07201
49 STO 93
```

T/C data

Frost heave

Sample ID

dh/dH

dh/dt

H

dH/dt

SP_o

Sets counters.

Program steps	Description
50♦LBL 04	
51 CLA 52 PRA 53 SF 12 54 ARCL IND 98 55 PRA 56 CF 12 57 CLA 58 PRA	Prints sample ID.
59 FIX 2 60 73.08001 61 STO 99	Sets depth counter.
62 CLA 63 " DEPTH" 64 ACA 65 " TEMP." 66 ACA 67 ADV 68 "MM " 69 ACA 70 " DEG C" 71 ACA 72 ADV 73 CLA 74 PRA	Prints heading for depth and temperature.
75♦LBL 03 76 RCL IND 99 77 ACX 78 2 79 SKPCHR 80 RCL IND 95 81 ACX 82 ADV 83 ISG 95 84 GTO 09 85♦LBL 09 86 ISG 99 87 GTO 03 88 CLA 89 PRA	Prints depth and temperature.
90 FIX 1 91 "FROST PEN.=" 92 ACA 93 RCL IND 97 94 ACX 95 " MM" 96 ACA 97 PRBUF	Prints frost penetration.
98 CLA 99 "FROST HEAVE=" 100 ACA 101 RCL IND 96 102 ACX 103 " MM" 104 ACA 105 PRBUF	Prints frost heave.
106 FS? 08 107 GTO 06 108 CLA	If flag 08 is set, disables printing of $\frac{dh}{dt}$, $\frac{dH}{dt}$, $\frac{dH}{dh}$ and SP_o.

```
109 "PEN. RATE="
110 ACA
111 RCL IND 92
112 ACX
113 " MM/DAY"
114 ACA
115 PRBUF
```

Prints frost penetration rate.

```
116 CLA
117 "HEAVE RATE="
118 ACA
119 RCL IND 91
120 ACX
121 " MM/DAY"
122 ACA
123 PRBUF
```

Prints frost heave rate.

```
124 CLA
125 FIX 2
126 "HEAVE RATIO="
127 ACA
128 RCL IND 90
129 ACX
130 PRBUF
```

Prints frost heave ratio.

```
131 CLA
132 FIX 1
133 "SEG. POT.="
134 ACA
135 RCL IND 93
136 ACX
137 " MM↑2/"
138 ACA
139 PRBUF
140 CLA
141 "DEG C-SEC"
142 ACA
143 FIX 3
144 ADV
145 CLA
146 PRA
```

Prints segregation potential.

```
147♦LBL 06
148 1
149 ST+ 96
150 ST+ 98
151 ST+ 90
152 ST+ 91
153 ST+ 97
154 ST+ 92
155 ISG 93
156 GTO 04
```

Increments counters.

```
157 FIX 2
158 CLA
159 PRA
160 "COLD BATH= "
161 ACA                      Prints bath 1 temperature.
162 RCL 40
163 ACX
164 "DEG C"
165 ACA
166 PRBUF
167 CLA
168 "WARM BATH= "
169 ACA
170 RCL 41                   Prints bath 2 temperature.
171 ACX
172 "DEG C"
173 ACA
174 PRBUF
175 CLA
176 "AMBIENT= "
177 ACA
178 RCL 42                   Prints ambient temperature.
179 ACX
180 "DEG C"
181 ACA
182 PRBUF
183 CLA
184 "ICE BATH= "
185 ACA
186 RCL 43                   Prints ice bath temperature.
187 ACX
188 "DEG C"
189 ACA
190 PRBUF
191 CLA
192 PRA
193 "TAPE POINTER= "         Prints tape location.
194 ACA
195 RCL 89
196 ACX
197 PRBUF
198 CLA
199 PRA
200 "END OF READING"
201 PRA
202 CLA
203 "----------------"       Prints END OF READING.
204 ACA
205 "----------"
206 ACA
207 PRBUF
208 CLA
209 PRA
210 RTN                      Returns to SCAN.
211 .END.
```

C26. <u>Program to summarize test results and shut down the freeze-thaw test</u>

```
12:56PM 30.04
01♦LBL "TEND"
02 CLRALMS                 •      Clears all alarms.
03 CLA
04 PRA
05 SF 12                          Prints end of test.
06 "END OF TEST"
07 PRA
08 CF 12
09 CLA
10 PRA
11 "  TEST SERIES: "
12 ARCL 00
13 ACA
14 PRBUF
15 CLA
16 PRA
17 "  CRITICAL "
18 "├FROST HEAVE"
19 PRA
20 CLA                            Prints headings for data summary.
21 "    RATES "
22 "├, MM/DAY"
23 PRA
24 CLA
25 PRA
26 "SAMPLE FREEZE"
27 "├  8    16"
28 PRA
29 CLA
30 "  ID     NO  "
31 "├HOURS HOURS"
32 PRA
33 CLA
34 PRA
35 0
36 1800
37 STO 88
38 32                             Finds 8-hour heave rates during first freeze on
39 STO 89                           tape cassette.
40 051.054
41 STO 87
42 XEQ "GET"
43 1152
44 ST+ 88
45 39.5
46 STO 89                         Finds 16-hour heave rates during first freeze.
47 055.058
48 STO 87
49 XEQ "GET"
```

```
50 2808
51 ST+ 88
52 80
53 STO 89
54 059.062
55 STO 87
56 XEQ "GET"
```

Finds 8-hour heave rates, second freeze.

```
57 1152
58 ST+ 88
59 88
60 STO 89
61 063.066
62 STO 87
63 XEQ "GET"
64 GTO 03
```

Finds 16-hour heave rates, second freeze.

```
65♦LBL "GET"
66 CLA
67 ARCL 00
68 RCL 88
69 6
70 +
71 SEEKR
72 10.010
73 READRX
74 RCL 10
75 RCL 89
76 X<Y?
77 GTO 11
78 72
79 ST+ 88
80 GTO "GET"
81♦LBL 11
82 RCL 88
83 52
84 +
85 SEEKR
86 RCL 87
87 READRX
88 RTN
```

Subroutine to read data from tape.

```
89♦LBL 03
90 FIX 1
91 "    1    "
92 ASTO 97
93 "    2    "
94 ASTO 98
```

Counters for freeze-thaw cycle.

```
95 051.06604
96 STO 90
97 001.00401
98 STO 99
```

Counters.

```
 99♦LBL 09
100 RCL 90
101 STO 95
102 097.09801
103 STO 96
104 CLA
105 ARCL IND 99
106♦LBL 06
107 ARCL IND 96
108 ACA
109 CLA
110 2
111 SKPCHR
112 RCL IND 95
113 ACX
114 2
115 SKPCHR
116 ISG 95
117 GTO 02
118 GTO 05
119♦LBL 02
120 RCL IND 95
121 ACX
122 ADV
123 ISG 95
124 GTO 02
125 GTO 05
126♦LBL 02
127 ISG 96
128 GTO 06
129♦LBL 05
130 CLA
131 PRA
132 001.001
133 ST+ 90
134 ISG 99
135 GTO 09
136♦LBL 07
137 END
```

Prints summary data.

APPENDIX D: DATA SHEETS FOR RECORDING AND PRESENTING RESULTS

FREEZE-THAW SAMPLE PREPARATION
DATA SHEET

Series No. _____ Material __________ Date _________

Sample No. _____ Specific Gravity (Gs) _____ Technician _________

Sample Specifications

Max. particle size _____ mm

% finer than .074 mm _____ %

% finer than .020 mm _____ %

Dry density _____ g/cc _____ lb/ft³

Water content _____ %

Compaction Mode

No. of layers _____

Height of layers _____

Blows per layer _____

Type of hammer _______

Weight of hammer _____

Compaction Data

Volume of mold, V_T = 2555 cc

Wt. of mold (rings + membrane + disk) = _____ gm.

Wt of mold + wet soil = _____ gm.

Wt of wet soil = _____ gm.

Wet unit weight, $\gamma_t = \frac{W_{s+w}}{V_T}$ = _____ gm/cc _____ lb/ft³

Water content of compacted soil

from 100 gram sample:

- tare no. _____
- Wt. of tare, W_T _____ gm.
- Wt. of tare + wet soil, W_{T+s+w} _____ gm.
- Wt. of tare + dry soil, W_{T+s} _____ gm.
- Wt. of water, W_w _____ gm
- Wt. of dry soil, W_s _____ gm.
- water content, ω _____ %

Dry unit weight, γ_d _____ gm/cc _____ lb/ft³

Sample Properties

Vol. of solids, $V_s = \gamma_d / (G_s \gamma_w)$ _____ cc

Vol of voids, $V_v = 1 - V_s$ _____ cc

Void ratio, $e = V_v / V_s$ _____

Porosity, $n = V_v \times 100$ _____ %

Saturation[1], $S = \omega \cdot G_s / e$ = _____ %

After Freeze-Thaw or Saturation

Slice No	Thickness mm	Tare No	W_T gm	W_{T+s+w} gm	W_{T+s} gm	W_w gm	W_s gm	ω %
1								
2								
3								
4								
5								
6								

Note: 1) to determine the degree of saturation after the saturation procedure, a separate sample must be used

FREEZE - THAW TEST RESULTS

SERIES NO

SAMPLE NO ________

COMPACTION PROPERTIES

Water Content ____ %

Dry Density ____ gr/cc

Porosity ____ %

Void Ratio ____

Degree of Saturation ____ %

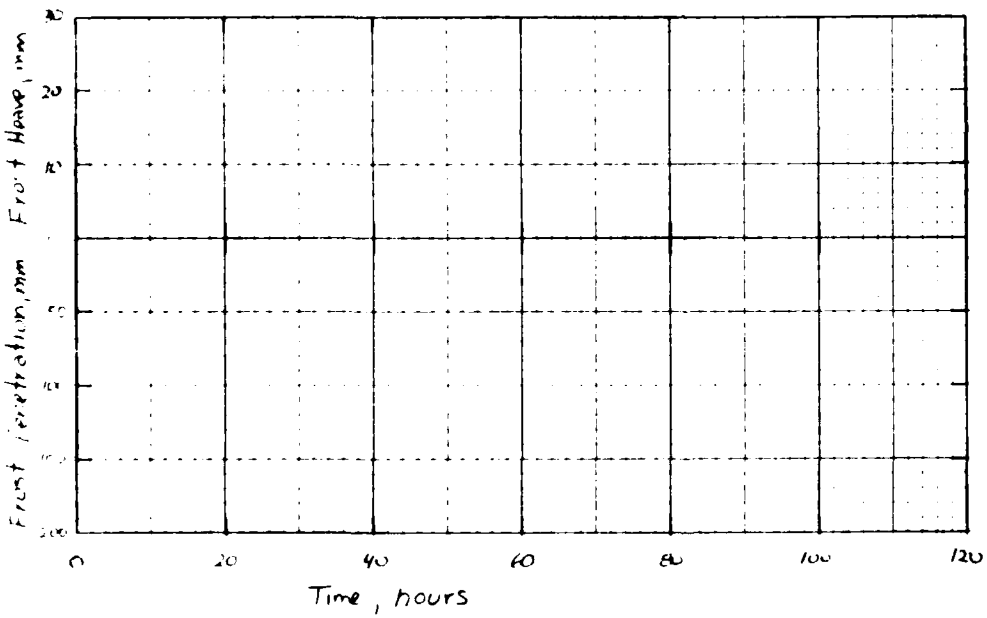
Freezing Point Depression ____ °C

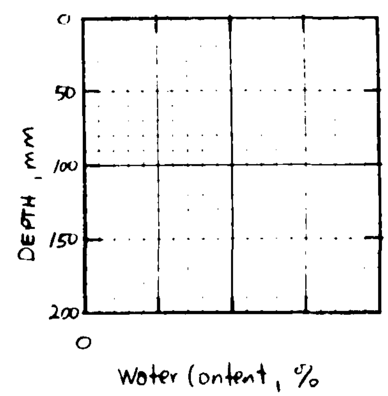
	Before Freezing	After Thawing
CBR, %		
w %		

TIME	FROST HEAVE RATE, mm/day 1ST Freeze	2ND Freeze
8-hour		
16-hour		

Frost * Susceptibility	Heave Rate mm/day	Thaw CBR %
Neg	< 1	> 20
VL	1-2	20-15
L	2-4	15-10
M	4-8	10-5
H	8-16	5-2
VH	>16	< 2

* circle frost susceptibility





DATE ________ TECHNICIAN ____________

END

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