REVIEW OF METHODOLOGY FOR LABORATORY ANALYSIS AND TESTING OF PERMAFROST

Prepared For:

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Geological Survey of Canada
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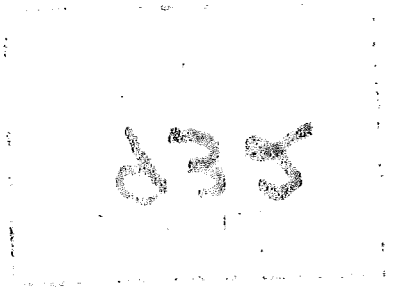
MARCH, 1983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EXECUTIVE SUMMARY

1. INTRODUCTION

The Geological Survey of Canada, (Department of Energy, Mines and Resources), commissioned Komex Consultants Ltd., in association with tti Geotechnical Resources Ltd., to conduct a review of the methodology associated with laboratory analyses and testing of permafrost. The purpose of the review was to provide an initial step in rationalizing the large number of test procedures that are available in both the published and unpublished literature.

In the long term , it is intended to develop standard, or reference tests, for permafrost materials. The present study has served to describe and evaluate some methods which are currently in practice for obtaining permafrost samples and the detailed test procedures being followed by recognized laboratories and researchers. Where possible, recommendations have been made concerning test procedures and equipment that appear to have particular advantages. Tests which can probably be standardized are indicated.

2. DRILLING, SAMPLING AND TRANSPORTATION OF SAMPLES

Standardized procedures for sampling in soil and rock have been prepared by the American Society For Testing and Materials (ASTM), as reported in a series of ASTM standards. However, special precautions must be observed in drilling and specialized equipment is frequently warranted when sampling in permafrost to ensure that the quality of the sample retrieved is commensurate with the types of laboratory tests that will be performed.

The mechanical properties of frozen ground are closely related to the temperature, as well as the temperature and stress history to which a sample has been subjected during drilling, sampling and transportation to the laboratory. Detailed laboratory measurements of the strength and deformation properties of frozen soils require high quality samples, with a minimum mechanical and thermal disturbance and moisture loss. Other types of tests, such as index tests and grain size distribution do not require high sample quality. Thawed samples are sufficient for testing of soils in their unfrozen state. The complexity of the laboratory test program, therefore, will affect the sample quality needed and, in turn, the choice of drilling and sampling technique.

The most common methods of drilling in permafrost are: (i) rotary drilling, usually using chilled brine solutions, diesel fuel, or compressed air; (ii) percussion drilling; (iii) augering; and (iv) vibratory drilling.

Permafrost samples may be obtained by a variety of methods, the selection of which depends on the quality required for subsequent testing. The best quality of samples may be obtained as block samples from test pits. However, for most purposes, it is necessary to depend on taking

samples from within a borehole. The least disturbance results from the use of core barrels, including a core barrel specially developed for sampling frozen ground by the United States Army Cold Regions Research and Engineering Laboratory (CRREL). Other commonly used methods of sampling permafrost, but which can result in considerable disturbance to the soil structure, are drive sampling, augering, and hand operated coring probes. A summary of available drilling and sampling techniques and anticipated sample quality for each technique is presented in Table 1.

The degree of care exercised in transporting a sample from the drill site to the field laboratory and subsequently to a city laboratory will depend on the types of tests planned, and particularly whether strength tests are to be performed. Partial melting of the cores should be avoided, since this will cause adhesion to sample containers, making extrusion difficult. Temperatures should be kept well below freezing or at the in-situ temperature to avoid major changes in the unfrozen water content. Saline permafrosts may drain at temperatures above -20°C. The temperature factor is especially important for silts and clays. Repeated freezing and thawing causes a hysteresis effect on physical properties. Samples should be kept at constant temperature or at steadily increasing or decreasing temperatures, thereby avoiding reversals in temperatures.

3. TESTING OF PERMAFROST CORES AND SAMPLES

3.1 GENERAL

3.2 CLASSIFICATION AND INDEX TESTS

a) Classification

Many of the standard classification procedures and index tests for unfrozen soils also apply to frozen soils. A full description of a frozen soil should include soil type, ice content and distribution, temperature and other characteristics affecting the sample's behaviour.

An extension of the Unified Soil Classification System can be used to describe frozen soils. In this system, the soil phase of the frozen sample is described by the USCS method, augmented by a description of composite ice-soil structure, if the ice is less than 25 mm in thickness, or of the ice itself if it is greater than 25 mm in thickness. This classification system includes guidelines for describing the ice phase, with respect to hardness, structure, colour, and admixtures.

b) Water Content

The bulk (total) moisture of a frozen soil sample may be determined by a standard American Society for Testing and Materials (ASTM) procedure. The volumetric quantity of ice in a sample of segregated ice has been traditionally estimated visually from the proportion of ice observed in the overall surface area of a permafrost sample. This method is prone to errors caused by individual procedures and lack of

precision. A more precise procedure for estimating the volumetric ice content is described by Savigny (1977).

The unfrozen water content of a frozen soil is dependent on a number of factors, the most important of which is temperature. The amount of unfrozen water decreases severely as the soil is cooled below 0°C. Other factors which influence the amount of unfrozen water are pressure, specific surface area of the soil, the chemical and mineralogical composition of the soil and pore water, and other physiochemical properties, such as cation exchange capacity. The following methods are used to determine the unfrozen water content:

- dilatometry
- adiabatic calorimetry
- X-ray techniques
- differential scanning calorimetry
- nuclear magnetic resonance
- time domain reflectometry
- acoustical

c) Bulk Density

The bulk density of frozen soils has been shown to be dependent on temperature, mainly because of the variation in unfrozen water and ice volumes. Conventional laboratory methods, including core and clod methods and the back-calculation of bulk density from dry density and moisture content measurements, involve the destruction of the sample. To avoid this problem, Haynes et al (1975) used a method similar to the standard specific gravity test (ASTM C97). In this test, the frozen sample is weighed both in air and while immersed in iso-octane at a temperature of -7°C.

d) Unfrozen Soil Index Tests

Many of the standard index and classification tests used for unfrozen soils are also applicable to permafrost soils after they have been thawed. Some 19 ASTM standard index and classification tests for unfrozen soils are identified in this section of the report.

3.3 SHORT TERM DEFORMATION BEHAVIOUR

The short term deformation behaviour of permafrost material is used to evaluate 'instantaneous' elastic properties of the medium. For activities such as ground fragmentation (drilling, excavation, etc.), the short term response is of dominant concern.

Most experimental research has been directed toward the long term (creep) deformation behaviour. Such behaviour is usually referred to as ductile or plastic. However, when loads are applied very rapidly, as in impact situations and especially at low temperature, frozen material may react in a very brittle manner.

Short term behaviour is usually investigated using biaxial and uniaxial and triaxial compression and tension tests. Considerably more research has been done on the short term behaviour of pure ice than on permafrost material. The ice component of permafrost is an extremely important factor governing overall material behaviour.

Procedures for the strength and short-term deformation testing of frozen soil, rock and ice have been developed by the following authors and organizations:

a) International Society of Rock Mechanics
b) IAHR Working Group on Ice Problems
c) Inland Waters Directorate, Department of the Environment
d) GEOTECH, Calgary
e) Vyalov (U.S.S.R.)
f) Michigan State University
g) U.S.Army Cold Regions Research and Engineering Laboratory
h) National Research Council of Canada
i) University of Alaska
j) University of Alberta
k) Terra Tek Inc., Salt Lake City, Utah
l) H.L. Jessberger

There are no generally accepted standard laboratory procedures for short term deformation tests in permafrost. Vyalov (1965) gives the most detailed procedure. Although now somewhat dated it is still generally followed by many investigators.

Because permafrost materials may exhibit a very wide range of strength, especially between warm permafrost, (near 0°C), and colder permafrost, (-5°C), testing equipment must accommodate a wide load range. A wide variety of test apparatuses are reported in the literature. Only recently have factors such as overall system stiffness, load platen configuration, etc., begun to be investigated. Hence, there is no apparent agreement within the research community on apparatus standards for short term behaviour tests.

It is the authors' opinion that the standard test procedures recommended by the International Society of Rock Mechanics (I.S.R.M.) and the International Association for Hydraulic Research (I.A.H.R.) for rock and ice respectively, provide a sound basis for a standard for short term deformation tests for permafrost. Finally, if brittle behaviour is anticipated, (e.g. cold permafrost, high pressure, and/or high loading

rates), the overall test system stiffness should be considered as it may affect the test results.

3.4 CREEP BEHAVIOUR

Tests of frozen soils may be conducted with various types of load conditions, including uniaxial and triaxial compression, uniaxial tension, shear and bending. The majority of researchers prefer the uniaxial creep test because of its simplicity and its potential applicability as a field test. Hence the majority of published creep data involves uniaxial testing. Very limited data exists for creep tests in shear, bending or tension.

Procedures for creep testing of frozen soils and ice have been developed by the following authors and organizations:

a) Vyalov (U.S.S.R.)
b) University of Alberta
c) Michigan State University
d) U.S.Army Cold Regions Research and Engineering Laboratory
e) Woodward-Clyde Consultants
f) Ecole Polytechnique, University of Montreal
g) Norwegian Geotechnical Institute

The majority of reported testing has been done on man-made rather than natural permafrost samples. Methodologies used in producing man-made permafrost samples are beyond the scope of this report. The final test specimen preparation and testing procedures, however, are the same irrespective of specimen origin.

Most creep tests are performed at temperatures near 0°C and accurate and reliable temperature control during long term tests is one of the most critical parameters. There is general agreement among researchers as to the optimal specifications for sample preparation and testing procedures. However, there remain a few areas where there appears to be no concensus within the scientific community on standard techniques. Test equipment is reasonably standard in its basic specifications but shows considerable variation in detail between research facilities. This is especially so with instrumentation and data acquisition systems.

Most researchers follow the general guidelines set out by Vyalov. Long term creep tests are generally performed on lever or dead weight test frames. Temperature control is achieved either by conducting the complete test in a walk-in cold room with very strict temperature control or by enclosing the test sample in a controlled temperature bath. Test systems vary somewhat between laboratories and also depending on the particular nature of the tests being performed.

3.5 DYNAMIC PROPERTIES

Foundations for structures incorporating vibratory loads (e.g. providing support for heavy machinery such as turbines) present special problems. Magnifications of motions due to structural resonances, fatigue, consolidation, etc. result from vibratory loading and are complicted by the presence of frozen and/or thawing soils. The response of such soils to vibratory loads differs significantly from that of unfrozen soils and this response needs definition.

Ground surface motions that occur during earthquakes are also influenced to a large extent by the characteristics of the underlying soil deposit under dynamic loading. Present analytical techniques to predict ground

surface motion require knowledge of the dynamic shear modulus and damping ratio.

Procedures for the dynamic testing of permafrost have been developed by the following organizations:

a) U.S.Army Cold Regions Research and Engineering Laboratory
b) Ruhr-Universitat, Bochum, F.R.G.
c) Michigan State University
d) University of Calgary
e) University of British Columbia
f) Queen's University

Dynamic testing of permafrost is, at present, in its infancy. Varying applications require testing over a wide range of frequencies to determine elastic properties (Young's modulus and Poisson's ratio). This necessitates the use of different apparatuses, sample preparation and testing procedures depending on end use requirements. Test standards will then probably have to be set for various frequency ranges, e.g. creep, low frequency (earthquake research), and high frequency.

3.6 THERMAL PROPERTIES

The position of the interface between thawed and frozen soil for a given surface-temperature regime depends on the thermal properties of the strata located above and immediately below the interface. These thermal properties are important parameters in the determination of frost and thaw penetration and are fundamental to all ground heat transfer problems. The basic thermal properties required for thermal analyses are thermal conductivity or thermal diffusivity, heat capacity, and latent

heat. These vary with phase composition and hence temperature, soil type, water content, porosity, degree of saturation, density and organic content.

For some engineering evaluations, published thermal properties may be adequate. However, in many instances, as well as for research needs, the direct measurement of thermal properties is required.

The following tests are described in detail in this report:

Thermal Conductivity Tests - thermal conductivity probes, U.S.A. CRREL and guarded hot plate test, U.S.A. CRREL; steady state method and line heat source probe technique, NRC of Canada; guard ring heater method, Continental Oil Co.; divided bar thermal conductivity apparatus, University of Saskatchewan; transient simultaneous measuring method, Katayama et al (Japan).

Specific Heat Test - differential scanning calorimeter, U.S.A. CRREL; calorimeter, P.J.Williams; low transient simultaneous measuring method, Katayama (Japan).

Thermal Diffusivity Test - sinusoidal temperature waves, U.S.A. CRREL; transient simultaneous measuring method, Katayama (Japan).

3.7 FROST SUSCEPTIBILITY AND FROST HEAVE TESTS

3.7.1 Frost Susceptibility Index Tests

Frost susceptibility index properties can be determined according to the following criteria and tests:

a) Particle size
b) Pore size characteristics
c) Moisture retention characteristics
d) Soil-water-ice interaction tests
e) Frost heave tests

Particle size criteria are the most common means of determining a soil's susceptibility to frost heave. Casagrande's proposed 'criteria' based on the percentage of particles smaller than 0.02 mm and 2 microns are still widely referred to.

Most of the frost susceptibility index tests, including a thaw-CBR test, may be applicable to soils subjected to light loads, usually roads and airfields. However, it is sometimes warranted to attempt to quantify the amount of heave that would occur under a defined set of soil, temperature and loading conditions. Rather sophisticated frost heave test equipment and procedures have been developed in recent years whereby both frost susceptibility index properties and quantitative estimates of frost heave may be obtained, as described in Section 3.7.2.

3.7.2 Frost Heave Tests

The following organizations have developed equipment and procedures for measuring frost heave:

a) Northwest Alaskan Pipeline Company
b) National Research Council of Canada
c) U.S. Army Cold Regions Research and Engineering Laboratory
d) French Regional Road Research Laboratory
e) Transport and Road Research Laboratory (England)
f) University of Washington

g) University of Alberta
h) Japan Gas Association

All of the tests developed by the above organizations have the capability of measuring frost heave in a controlled laboratory environment. Some of the tests (U.S.CRREL, British TRRL, French RRRL) are treated as index tests of frost susceptibility and no attempt is made to determine what the actual heave would be under field conditions. Other tests (Northwest Alaskan Pipeline Company, University of Alberta) attempt to control enough of the variables affecting frost heave that a quantitative prediction of the magnitude of frost heave in the field is possible. None of these tests has been validated sufficiently in the field to confirm its potential for use as a universal frost heave test. However, the Northwest Alaskan Pipeline company is presently engaged in a comprehensive program of both laboratory and field frost heave tests. If satisfactory correlations are established over the next few years between the laboratory predictions and the field measured heaves for a variety of soil types, this tests procedure may well be worthy of consideration for implementation as a test standard, perhaps with modifications to incorporate the best features of some of the other tests now in use.

3.8 THAW CONSOLIDATION TESTING

When thawing occurs in permafrost, water is liberated and pore pressures are generated. The strength of the thawed soil depends on the pore pressure and the settlement rate will vary with pore pressure dissipation. A knowledge of the above conditions is essential to quantitative foundation analysis.

Procedures for thaw consolidation testing have been developed by the following organizations:

a) University of Alberta
b) Woodward-Lundgren and Associates
c) U.S. Army Cold Regions Research and Engineering Laboratory
d) Woodward-Clyde and Associates
e) Northwest Alaskan Pipeline Company and Shannon and Wilson Consultants

Although it is possible to provide a high degree of sophistication in the performance of a thaw consolidation test (pore pressure and temperature measurements, controlled thaw rate), a fairly simple test apparatus and procedure is probably sufficient for most purposes. Because of the large amount of variation in ice contents in many soils, the test should be regarded more as an index test, rather than as a precise means of estimating thaw strain.

Because of its detailed description and essential simplicity, the test procedure used by Shannon and Wilson Inc. for the Northwest Alaskan Pipeline Company should be considered as a reference test. The test apparatus and procedures reported by the University of Alberta, which permit controlled thaw rates and temperature measurements, are probably unnecessarily elaborate for most commercial applications, although they should be considered in thaw consolidation research activities.

3.9 ELECTRICAL PROPERTIES

Electromagnetic geophysical techniques for mapping permafrost and the electrical grounding of various types of machines and electrical equip-

ment in permafrost areas require a knowledge of frozen ground electrical properties, such as the dielectric constant and electrical conductance and resistivity. These parameters are sensitive to soil's molecular configuration, composition, texture, porosity, temperature, water content, and electrical frequency.

Current flow under an electrical gradient occurs almost entirely through the unfrozen water films. In general, frozen soil cannot be regarded as a good conductor. Ice and mineral particles are relatively poor conductors and the transition layer between them causes frozen soil to have a conductance factor 5 to 10 times less than the same soil in an unfrozen state.

Little information is available on laboratory studies of electrical properties of permafrost, although this information can be very important in certain applications. The data base, at this time, appears inadequate to define standard test techniques and equipment.

3.10 SOIL CHEMISTRY, MINERALOGY AND PORE WATER CHEMISTRY

A knowledge of the chemical and mineralogical constituents of the solid and water fractions of a soil sample can be an important aid in the interpretation of the physical properties and mechanical behaviour of a soil, as determined by the various tests described in this report.

Test procedures developed at the University of Toronto, U.S.Army CRREL, Geological Survey of Canada, and the University of Saskatchewan are included in this report.

3.10.1 Soil Chemistry

The chemical composition and behaviour of a soil will affect its engineering performance. The common index tests do not always provide enough information with respect to the effects of chemical behaviour. Clays are particularly sensitive to the chemical composition of the interstitial and pore waters. Some of the basic tests to establish soils chemistry are referred to in the text, including a procedure to identify dispersive clays.

3.10.2 Soil Mineralogy

A general procedure for mineralogical analysis of a soil sample is presented. Microscopic methods are commonly used to identify the mineralogy of the coarse fraction (retained on No.200 sieve). X-ray methods and differential thermal analyses may be used to identify the composition of the clay and silt fraction. The cation exchange capacity, as determined from chemical, X-ray, and radioactive methods, may also be used to correlate with the mineralogical composition of the silt and clay fraction of a soil.

3.10.3 Pore Water Chemistry

The chemistry of the pore or interstitial waters affects many of the properties of a frozen soil. The presence of salt ions has the most dramatic effect, by lowering the freezing point of the soil. The chemical constituents of pore water are affected by temperature. This is of particular importance for frozen soils at temperatures near 0°C. For this reason, it is recommended that the extraction of pore water take place at or near the drilling site, preferably no later than 2 hours after core recovery. Measurements of pH and bicarbonate

concentrations should be made immediately so as to obtain values near to the in-situ concentration.

Methods for laboratory determination of the chemical constituents of porewater are presented in this report.

3.11 ACOUSTICAL AND GEOPHYSICAL PROPERTIES

Velocities of various subsurface materials are commonly obtained during field seismic surveys. Interpretation of results can be difficult in many cases if the condition of the materials is not known.

Either resonance or pulse transmission techniques are usually used in the laboratory to determine the dynamic properties of frozen soil or rock. The pulse transmission method is directly comparable with seismic travel-time determinations, apart from the difference in wave-length.

Velocities are higher in frozen soils or rocks than in the same unfrozen material. The largest increase in compressional wave velocity from the unfrozen to the frozen state occurs in unconsolidated sediments.

Test procedures developed by Hardy and Associates, Calgary, Geological Survey of Canada, U.S.Army CRREL, and the University of Saskatchewan are included in this report.

Surprisingly little published data is available on laboratory studies in this area although it is important both for general seismic permafrost mapping and for proper log interpretation of offshore wells in areas such as the Beaufort Sea. Although little test data is available on permafrost, the pulse technique has been widely used in rock mechanics

for many years and standard test procedures from this area should also be applicable to permafrost testing.

3.12 HYDRAULIC CONDUCTIVITY TESTING

The measurement of hydraulic conductivity characteristics of frozen soils is often made in conjunction with consolidation and frost-susceptibility tests. Procedures have been developed at Carleton University, the University of Alberta, and U.S. CRREL and are generally variations of the constant and falling head test procedures commonly used for unfrozen soils. Solutions of lactose or polyethylene glycol were used as the permeating fluid in order to overcome suction effects. The use of these fluids caused some thawing at one end of the sample, for which the frozen sample length should be corrected.

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1. INTRODUCTION AND TERMS OF REFERENCE

More and more individuals and organizations have been working in the permafrost areas of Canada, on problems of a geotechnical nature. These include federal, provincial and territorial government agencies, consulting engineers, petroleum and mineral exploration, production and transportation companies and university professors and students. Most of these organizations have included sampling and laboratory testing in their programs. The laboratory testing has been undertaken in field laboratories adjacent to the sampling site, at laboratories in northern towns and camps, and in southern Canada. While various standard geotechnical and other tests have been performed on many samples, the nature of the permafrost material has demanded modifications to some of the standard test procedures and the development of new tests. Rather different procedures have been developed in different laboratories, with the result that it is often difficult to make meaningful comparisons between test results from one laboratory and another. More over, there has been little validation from field behaviour of data obtained in the laboratory, so that the meaning of many laboratory-based tests are still unclear (Morgenstern, private communication, January, 1983).

As an initial step in rationalizing the large number of test procedures that are available in both the published and unpublished literature, the Geological Survey of Canada,(Department of Energy, Mines and Resources), commissioned Komex Consultants Ltd., in association with tti Geotechnical Resources Ltd., to conduct a review of the methodology associated with laboratory analyses and testing of permafrost.

In the long term, it is intended to develop standard, or reference tests, for permafrost materials. The objective of the present study has been to describe and evaluate methods which are currently in practice

for obtaining permafrost samples and the detailed test procedures being followed by recognized laboratories and researchers. Where possible, recommendations have been made concerning test procedures and equipment that appear to have particular advantages. Tests which can probably be standardized are indicated. However, it is beyond the scope of the present study to provide recommended test equipment and procedures for these tests.

Section 2 of the Report describes drilling, sampling and transportation of permafrost samples, while Section 3 describes the various laboratory tests. Appendix A summarizes in tabular form documented case histories of drilling and sampling techniques for permafrost. Appendix B is an annotated bibliography of reports and publications concerning the subject matter of this report. The bibliography contains many publications which are not referenced in the text of the report, and is intended as a collection of information on permafrost sampling and testing.

The Contract, under which this review was performed, was issued by the Department of Supply and Services, Serial Number OSQ82-00022, dated May 13, 1982.

1.1 REPORT FORMAT

As test equipment and procedures are referred to extensively in the report, a format has been adopted whereby quoted material is typed at single line spacing with an increase in margin indentations. Text prepared by the authors is spaced at 1 1/2 lines, with a smaller marginal indentation.

1.2 STUDY PARTICIPANTS

The companies and individuals who participated in this study are identified as follows:

a) Joint Venture Companies

Komex Consultants Ltd.	Mr. F. B. Claridge
	Mr. D. G. Fisher
	Mr. B. H. Conlin
tti Geotechnical Resources Ltd.	Dr. W. F. Bawden
	Dr. D. S. Masterson
	Mr. S. J. Green

b) Reviewers

Professor N. R. Morgenstern, University of Alberta
Mr. K. A. Linell, Consultant
Mr. F. H. Sayles, U.S.Army, Cold Regions Research and Engineering Laboratory
Professor B. Ladanyi, Ecole Polytechnique, University of Montreal

In addition, considerable assistance was gained from various meetings and discussion with personnel from the following organizations:

Geological Survey of Canada, Department of Energy, Mines and Resources (sponsoring agency)
Earth Physics Branch, Department of Energy,Mines and Resources

National Research Council of Canada
United States Army, Cold Regions Research and Engineering Laboratory
Carleton University, Department of Geography
Gulf Canada Resources Inc.
Dome Petroleum Ltd.
Hardy Associates Ltd.
Northwest Alaskan Pipeline Company
Mobile Augers and Research Limited

2. DRILLING, SAMPLING, AND TRANSPORTATION OF SAMPLES

2.1 GENERAL

Current practices with respect to drilling and sampling techniques for frozen ground are briefly reviewed and commented on in this report. Particular attention is paid to the effects of each technique on sample quality and permafrost behaviour in laboratory tests. Methods for the transportation and storage of cores are also discussed.

2.2 STANDARD PRACTICES FOR DRILLING AND SAMPLING OF UNFROZEN SOILS

Conventional procedures for drilling and sampling of unfrozen soils are well known, and are described in American Society for Testing and Materials (ASTM) Standard D420-69, "Standard Recommended Practice for Investigation and Sampling Rock and Soil for Engineering Purposes". This document outlines the equipment and procedures for a subsurface investigation.

Sampling procedures for soil and rock which have been standardized by ASTM (1982) are listed below.

D1452-80	Soil investigation and sampling by auger borings
D1586-67(1974)	Penetration test and split-barrel sampling of soils
D1587-74	Thin-walled tube sampling of soils
D2113-70(1976)	Diamond core drilling for site investigation

D2944-81 Sampling processed peat materials

D3550-77 Ring-lined barrel sampling of soils

The applicability of these and other methods to the sampling of permafrost is discussed in the following sections.

2.3. ASPECTS OF PERMAFROST BEHAVIOUR AFFECTING SAMPLING

The choice of drilling and sampling techniques in permafrost is important, since samples must be of sufficient quality for the required laboratory testing.

The mechanical properties of frozen ground are dependent on temperature, as well as other factors such as soil mineralogy and pore fluid composition. The strength characteristics of the soil are crucial to the selection of the drilling and sampling techniques. Laboratory experiences have shown that below a threshold temperature of -4°C or -5°C, the strength of frozen soil approaches that of pure ice, which is comparable in magnitude to soft bedrock (Hvorslev and Goode,1963). Above -4°C, however, a large amount of unfrozen water is present, thus decreasing the strength, until it reaches that of the unfrozen soil near 0°C. The choice of drilling and sampling techniques and equipment is heavily dependent on the ground temperature. The mechanics of drilling and coring in frozen ground are discussed in detail in several papers by Mellor (1975b, 1976a, 1976b, and 1977). These factors are summarized by Mellor and Sellmann (1975) and are discussed in Section 2.4.2 of this report.

Variations in the moisture content and the redistribution of moisture have a profound effect on the behaviour of frozen ground. Moisture

loss and redistribution is caused by temperature gradients and humidity effects such as evaporation and sublimation (Baker, 1976). A significant amount of unfrozen water is present in soil even at very low temperatures, however, the unfrozen moisture content increases dramatically above -4°C (Hvorslev and Goode, 1963). Since the effect of temperature reversals on frozen soil properties is not well understood, care should be taken to ensure that soil samples are protected from large temperature and humidity gradients in their journey from the borehole to the laboratory test. Sample disturbance has been found to affect the magnitude of thaw strain as measured in thaw consolidation tests (Smith et al, 1973).

Detailed laboratory measurements of the strength and deformation properties of frozen soils require high quality samples with a minimum mechanical and thermal disturbance and moisture loss. Other types of tests, such as index tests and grain size distribution do not require high sample quality. Thawed samples are sufficient for testing of soils in their unfrozen state. The complexity of the laboratory test program, therefore, will affect the sample quality needed and, in turn, the choice of drilling and sampling technique.

A system for the evaluation of sample quality was developed to aid in the choice of sampling method. This system is loosely based on that developed for unfrozen soils by Idel et al (reference unknown), and is presented in Table 2.1.

2.4 DRILLING METHODS

2.4.1 Introduction

The choice of a drilling method is largely dependent on the scope and objectives of the project, the quality, size and depth of sampling required, and site conditions, including ground conditions, economics, accessibility, ground and air temperature, and seasonal variations in the above factors. The advantages and disadvantages of the various drilling methods now in use are discussed in the following sections.

2.4.2 Choice of Drilling Equipment

Mellor and Sellmann (1975) outline several factors which effect the efficiency of a drilling system in permafrost. Recommendations on drilling procedures are made, based mainly on theoretical studies of drilling mechanics made by Mellor (1975, 1976a, 1976b, 1977).

Drilling systems embrace three functions:

1. Penetration of the ground material.
2. Removal of surplus material.
3. Stabilization of the hole wall.

Penetration may be accomplished by mechanical (rotary, percussive or vibratory drilling), or thermal (melting) methods.

Material removal may be made by direct lifting of cuttings or cores, lifting of cuttings by fluid suspension, lateral displacement (in compressible materials) and dissolving cuttings. Hole wall stabilization may be achieved by using casings or high density fluids (bentonite).

The interrelations of these methods are summarized in Fig.2.1.

A major factor in the choice of drilling equipment is the accessibility to the site. Lightweight drills have a distinct mobilization advantage over heavier drills, but generally produce poorer quality samples. Kurfurst (private communication) found that lightweight 'Winkie' drills can be used to 30 ft depth in relatively fine grained materials, with inexpensive labour, but produces relatively poor quality samples. A Ranger drill may be used for deeper sampling. Ladanyi (private communication) also recommends the use of light drilling equipment for easy transport.

GSC is now using a drill mounted on an All-Terrain Vechicle (ATV) (Nixon, 1978, Veillette and Nixon, 1975). The ATV drill allows rapid drilling at shallow depths, and is fast and maneuverable. It is far superior to snowmobiles as a means of transporting drilling equipment.

2.4.3 Rotary Drilling

Rotary drilling is commonly used in permafrost investigations. This method involves the rotation of a cutting tool, or bit, under constant normal pressure. A means of removing drill cuttings is essential and is usually provided through the use of drilling fluids. Many agencies (GSC, CRREL) prefer dry coring methods where possible.

The success of rotary drilling is highly dependent on the skill of the operator. Although portable, lightweight drills are available, rotary equipment is often bulky, making transportation between drilling sites difficult. Conventional rotary drilling and drive sampling techniques have been used to depths of 100 m in the Beaufort Sea (Chamberlain, 1981).

The choice of an appropriate drilling bit is essential to the success of a rotary drilling program. Bits made of hardened steel or various metal alloys, such as tungsten carbide, are suitable for frozen, fine grained soils, but wear significantly if hard strata, pebbles or boulders are encountered. In these cases, the use of diamond bits is preferred. Diamond bits have been used with great success in the drilling and continuous coring of frozen coarse gravels, stony tills and bedrock, but are not suitable for fine grained or unfrozen materials, since the high rotational speeds required can cause the sample to thaw.

2.4.4 Drilling Fluids

Rotary drilling of soil and rock requires a drilling fluid to facilitate the cutting of the material, and to carry the chips from the bit to the ground surface for disposal. In permafrost, the choice of a drilling fluid depends on its ability to operate efficiently at low temperatures while not contaminating the sample or the surrounding soil. Good circulation of the fluid is necessary around the drilling bit and upwards to the surface, while contact between the fluid and the sample must be minimized.

Water has long been used in the drilling of soil and rock. The suitability of water for the drilling of frozen ground, however, is questionable, because of the difficulty in cooling water to below $0^{o}C$ in order to minimize thermal disturbance. Samples with a large ice content are often 'etched' when in contact with water which is at a temperature only slightly below $0^{o}C$.

Water can be used effectively as a drilling fluid for frozen soils, provided that only minimal contact is allowed with the core, and the rate of penetration into the permafrost is rapid. Samples obtained

Goode, 1963). The refrigeration of compressed air is difficult and costly, especially in warm weather. Circulation problems around the drilling bit have also been reported (GSC), and penetration rates are slow. Moisture can freeze in lines and clay cuttings will tend to ball up and jam.

2.4.5 Percussion Methods

Percussion drilling involves alternately raising and dropping a weight to break the material at the bottom of the drill hole. Broken fragments are removed by use of a bailer or drilling fluids. Many variations on this method exist, such as direct raising and dropping of the bit, and the drop of a hammer onto a bit already at the bottom of the hole. Combinations with rotary drilling are also used. Mobile Augers (1978) describe the use of a combination cable tool - rotary drill. This method allows cable tool drilling and casing driving through difficult strata, and switching to the faster rotary method where hole conditions permit.

The percussion method is very slow, and requires frequent repair and replacement of parts damaged by the hammering motion. It is useful, however, to break through hard strata, where augering and rotary drilling fail, and also for providing large diameter holes (Morgenstern, private communication).

2.4.6 Augering Methods

Borings in fine grained, frozen soils can often be made with relative ease by dry augering. This method has the advantage of the removal of cuttings without a drilling fluid. There are two types of augering (Mobile Augers, 1978): foundation boring, in which large diameter holes may be drilled to shallow depths (for pile founations), and continuous

through this process are useful for determining ice contents, grain size distributions, and other index properties.

Salts may be dissolved in water in order to lower its freezing point. The effectiveness of salt solutions as drilling fluids is heavily dependent on concentration. Some salts such as sodium chloride and calcium chloride, significantly lower the freezing point of the water, but may be highly corrosive to drilling equipment (Mobile Augers, 1978). Salt solutions can be used effectively with minimal sample contamination in conjunction with double or triple tube core barrels with face discharge bits, if salt concentrations are below 10% and temperatures are kept near to that of the soil (Roggensack, 1979). Drilling muds, or slurries, may be used for drilling, but because of their high viscosity, circulation can be difficult.

There are many reports on the use of diesel fuel as a drilling fluid. Diesel is easily cooled in cold weather and may be used to obtain good samples of impervious materials. Surface contamination of the cores, however, may occur, and the toxic nature of diesel fuel may cause health and environmental concerns (Isaacs and Code, 1972). Diesel fuel forms a 'sludge' with chips of sand and silt which may block circulation (Veillette and Nixon, 1980).

Manufactured organic fluids, such as Therminol 55 (Isaacs and Code, 1972), have been used successfully in drilling permafrost. This fluid is more viscous than diesel fuel, thus reducing surface contamination of cores, and is biodegradable, alleviating environmental concerns. Some refrigeration problems have been found with Therminol, however, and the fluid is expensive.

The use of compressed air as a drilling medium in frozen ground has been discouraged by several field experiences (Lange, 1963, Hvorslev and

flight augers, which consist of sections of augers joined together, and in which cuttings are automatically conveyed to the surface. Continuous flight augers are commonly used in soil investigations (Ladanyi, private communication, Nixon, 1978, Mobile Augers, 1978).

Continuous flight augers may be either solid-stem or hollow-stem. Solid steam augers require that the entire auger assembly must be pulled from the ground so that cores may be obtained. The hoisting of continuous flight augers can be difficult and slow (Nixon, 1978). Hollow stem augers allow the use of most sampling methods without retraction of the augers. They are used extensively in granular soils in Alaska by CRREL, both along the Alaska pipeline route, and in sampling undersea permafrost (Sellmann, private communication).

High penetration rates are possible with augering in fine grained soils. However, augering in cold temperature frozen soils, and the presence of pebbles, boulders, and rock can cause excessive wear and failure of the augering bits. Refusal in hard strata is common. Augering is also difficult in partially frozen soils, since ice tends to build up on the cutting shoe of the auger, and cuttings frequently adfreeze to the auger. CRREL has found that a clean cutting edge is essential for successful augering. Adjustments in the cutting edge may be made to achieve this condition (Linell, private communication).

2.4.7 Vibratory Drilling

Vibratory drilling of permafrost is a recent development in North America. The principle is to transmit a large force at a high frequency, which causes liquefaction of the materal around the drill pipe. Rapid penetration is possible in fine grained, frozen soils and soft bedrock, but difficulties arise when pebbles and boulders are encountered. An important advantage of the vibratory method is the easy

removal of drilling and sampling tools which become stuck in the drill hole due to adfreeze, or collapse of the hole walls. Vibratory drilling is practical in locations where surface water is scarce.

Roggensack (1977) found that samples obtained with vibratory sampling techniques are not suitable for strength or consolidation testing, because of severe mechanical disturbances.

2.5 PERMAFROST SAMPLING

2.5.1 Introduction

The choice of a sampling technique for frozen soils depends on a number of factors:

(i) size and quality of samples required for the laboratory program
(ii) depth of sampling
(iii) mean temperature and seasonal fluctuations
(iv) available drilling equipment

Equipment may vary greatly as a function of these factors. Type and approximate location of major soil strata may be found from examining chips from augered holes, while samples obtained by a more sophisticated method may be necessary for the determination of strength and deformation properties and location of fine stratification.

CRREL (Sellmann and Brockett, private communication) favours sub-sampling in the laboratory of larger samples in the field, in order to obtain highly undisturbed samples for strength testing. Typically,

two-inch diameter sub-samples are taken from three-inch diameter cores from the field by miniature core barrels.

Various sampling methods for frozen ground and their applicability to different conditions are discussed in the following sections, and are summarized in Tables 2.2 and 2.3. Specific examples from the literature of the use of various methods of sampling are presented in Appendix A.

2.5.2 Drive Sampling of Permafrost

Drive sampling involves the hammering of a solid or split hollow tube sample into a material. Although the percent core recovery is usually very good in drive sampling of fine grained soils, samples are likely to be subject to a great deal of mechanical disturbance caused by the hammering action.

At CRREL, drive sampling is generally utilized to a depth of 25 ft, provided that a reduction is made in sample diameter with depth (Linell, private communication). Drive sampling is applicable to every soil type to obtain highly disturbed samples suitable for stratigraphy and moisture contents. Experiences at GSC and CRREL have shown that drive sampling of permafrost is possible at temperatures greater than $-3^{o}C$. (Heginbottom, private communication; Linell, private communication).

The use of drive sampling to obtain high quality samples of permafrost is discouraged by NRC. In general, if a tube cannot be pushed through the permafrost, another method of sampling should be attempted. Drive sampling is often accompanied by Standard Penetration Tests in unfrozen soils, but in permafrost, they are difficult to interpret due to presence of ice. However, results may be obtained with a static-cone

penetrometer (Blouin, et al, 1979). Similar results have been obtained by Gulf (Jeffries and Graham, private communication).

Drive sampling may be used effectively in sampling frozen fine grained and organic soils. The occurrence of pebbles and boulders may cause structural damage to thin-walled tubes, so that thick-walled tubes are often required for permafrost. Cores of coarse and gravelly materials are difficult to obtain, since the hammering action often destroys the soil-ice structure. Disturbed samples of these soils may be obtained through the use of a 'core-catcher' within the tubes.

2.5.3 Augering Samplers

In addition to their use in drilling methods, augers may be used to sample permafrost. An important development in the sampling of frozen soils has been the CRREL ice-coring auger. Originally designed as a hand tool for coring ice by the US Army Corp of Engineers Cold Region Research and Engineering Laboratory (CRREL), (Ueda et al, 1975), the ice-coring auger has been modified for use with drilling methods. The barrel is turned into the ground without the aid of a drilling fluid, and may be run as the lower 3 ft of a continuous flight auger. The CRREL barrel has recently been used in conjunction with vibratory drilling methods (Mobile Augers, 1978). Although it is best suited for sampling fine grained, frozen soils, organic soils, ice and snow, the CRREL auger may be fitted with hardened bits at the auger tip and thickened in sections for use with rotary drills to core gravels and hard tills.

Cores obtained with the CRREL auger are short, with respect to the length of the barrel. It is often difficult to break the core from the base of the borehole, and the CRREL auger often jams on its cuttings, since there is limited room between the outside diameter of the barrel

and the walls of the hole (Veillette, 1975). As with other augers, difficulties are encountered with the presence of unfrozen water.

Despite its shortcomings, the CRREL ice-coring auger has found wide acceptance as a coring tool for frozen soils. Modified versions of the CRREL barrel (see Fig.2.2) are used in Canada by GSC (Heginbottom, private communication), Mobile Augers and others.

Modifications made to the CRREL ice auger have been made at the University of Alberta, as described below (Roggensack, 1977).

> The core barrels used to obtain samples for the laboratory program described in the body of this thesis were all constructed to provide a 10 cm (4 inch) inside diameter. Modifications to models which had been used previously included:
>
> 1) Eliminating the outside drive collar at the top of the barrel, thus promoting the movement of the cuttings up the flites to where they could be reservoired.
>
> 2) Redesigning the cutting teeth and using case-hardened steel instead of attaching tungsten carbide inserts to the leading edge.
>
> 3) Providing a convenient bayonet drive connection on barrels used in hand sampling operations.
>
> 4) Constructing the core barrels from stainless steel tubing.
>
> 5) Thickening, and thereby strengthening the core barrel at its top by providing an inside collar where the drive head is attached.
>
> To promote rapid core barrel penetration in fine-grained permafrost soils, the angle between the front surface of the cutting edge and surface being cut was set at 55°. A positive back clearance angle of between 30° and 35° was adopted. With this configuration, cutting was most effective when a back clearance of approximately 0.5 cm (0.2 inches) was maintained. A small inside clearance of up to 0.03 cm (0.01 inches) was provided by setting the cutting teeth to overlap the inside

surface of the core barrel. These teeth were made from case-hardened Keewatin tool steel and exhibited good wear characteristics when cutting fine-grained frozen soils. In sandier materials, it remained necessary to use tungsten carbide inserts soldered onto the cutting face, but a great deal of breakage was experienced when stones were encountered. More recent experience with seismic grade inserts had indicated that their greater durability renders them satisfactory for this particular application. Some of the hardened teeth were field-sharpened with a grinder when the cutting edge became dull. They proved to be quite durable in cutting through soil which contained a few pebbles, and suffered less breakage than the earlier carbide inserts had. A core catcher was not provided since cuttings normally jammed into the gap between the core and the inside of the barrel. Inside friction built up until the core broke off, and also held it in the barrel during extraction from the borehole. Whenever a mechanical break did not occur during the coring run, the cores were separated at the cutting face by jarring the core barrel or pushing a wedge into the annulus to snap the core with a cantilivering action. The core barrel was than run down the borehole to extract the loose piece of core.

2.5.4 Core Barrels

Core barrels are commonly used in conjunction with rotary drills for the purpose of permafrost sampling. Although they were developed to core bedrock (mainly for mineral exploration), core barrels have been used with some success in sampling frozen soils. An excellent review of core barrel types and their applications is given by Veillette and Nixon (1980). A list of standard core barrel sizes is presented in Table 2.4.

Single tube core barrels are commonly used for coring compact rock. The drilling fluid must pass between the tube wall and the core, thus washing the sample. In frozen soils, this direct fluid contact may seriously erode the sample, often destroying it completely. Samples are also subject to direct contact with the rotary tube, causing a great deal of abrasion and mechanical disturbance. For these reasons, single

tube core barrels are effective only for hole advancement, and are commonly used to drill the first few metres of a borehole, before a switch is made to other core barrels. Veillette and Nixon (1980) report that single tube core barrels may be used successfully to core frozen peat at shallow depths.

Double tube core barrels are of either the 'rigid' or 'swivel' type. In the rigid type double tube, the inner tube is attached to the outer tube, and rotates with it. The drilling fluid passes between the tubes, contacting the core only at the bit. As with the single tube, cores of frozen soil are greatly disturbed through contact with the rotating tube.

Double tube-swivel type core barrels represent a significant improvement. The inner tube is separated from the outer tube, so it can remain stationary, protecting the core from abrasion and mechanical disturbance. Some inner tubes are adjustable so the fluid contact with the core is minimal. This core barrel is effective in sampling cold-temperature frozen soils, especially coarse grained soils with cobbles and boulders, and bedrock. It is not recommended, however, for coring warm-temperature frozen fine grained soils and unfrozen gravels, because of potential ice buildup on the core barrel shoe. This is also a problem in sampling frozen peat (Nixon, 1978).

The triple-tube, swivel-type core barrel is similar to the double tube, except that a split tube is placed within the inner tube. This facilitates the handling of cores at the surface, but smaller-diameter cores are obtained.

The disadvantage of the above core barrels is that the entire assembly must be retracted from the borehole each time a core is to be retrieved, increasing the possibility of mechanical and thermal disturbance. The

wireline core barrel was developed to overcome these difficulties. The inner tube of a double or triple tube core barrel may be retracted to the surface for removal of the sample, leaving the outer tube and drilling bits in the ground at ground temperature. This process makes coring at greater depths more practical. The wireline technique requires heavy drilling equipment, thus presenting some transportation problems, however, the process has been used to successfully core permafrost on numerous occasions (Lange, 1963, Isaacs and Code, 1972). Although wireline core barrels are not standardized, common sizes have been developed, as presented in Table 2.4.

2.5.5 Test Pits

Relatively undisturbed block samples of frozen soils may be obtained by digging test pits (Kitze,1956). Intact permafrost may be examined visually by this method. Test pits may be used effectively to sample frozen soils, but are limited to shallow depths, and are difficult below the water table in warm weather. Excavation of test pits requires power equipment, which may not be readily available on remote sites, or manual excavation, which is laborious and time-consuming. Excavation in a foundation area may promote undesirable thawing in the subsurface permafrost (Kitze,1956).

2.5.6 Hand-Coring Methods

Permafrost may be sampled to shallow depths by hand-held and powered coring augers and probes. The frost table probe, which is simply a solid metal rod, is the simplest of these tools. It may be used to locate the depth to the top of permafrost in fine-grained soils, but cannot penetrate coarse materials. The modified Hoffer probe (Veillette and Nixon,1980) can be used in warm weather to obtain small diameter (2.5 cm) cores of fine grained soils and peat. Small versions of the

CRREL ice coring auger may be used to obtain small diameter cores at shallow depth (Viellette and Nixon 1980; Nixon 1979).

2.6 POST-SAMPLING TREATMENT OF PERMAFROST CORES

2.6.1 Introduction

The handling of permafrost cores after sampling, their transportation to laboratory facilities, and storage until time of testing should be performed so that minimal physical and thermal disturbance occurs. Ideally, in-situ moisture and temperature conditions would be maintained during this period. However, this would be very expensive, and warranted only in specific situations, i.e. research purposes.

In this section, the effects of various factors on permafrost sample handling will be discussed. Current practices with regards to extrusion, handling, transportation and storage of samples are discussed.

2.6.2 Factors Affecting Sample Handling

The procedure followed for transporting a frozen soil is affected by its strength, classification, ice content and distribution, and temperature (Aitken, 1970). Partial melting of the cores should be avoided, since this will cause adhesion to sample containers making extrusion difficult. Temperatures should be kept well below freezing or at the in-situ temperature to avoid major changes in the unfrozen water content (see Section 3.2.2). Saline permafrosts may drain at temperatures above $-20^{o}C$. The temperature factor is especially important for silts and clays. Repeated freezing and thawing may cause a hysteresis effect on physical properties. Samples should be kept at constant temperature or

at steadily increasing or decreasing temperatures. Reversals in temperatures should be avoided (Baker,1976). The "thermal-shocking" of samples with dry ice should also be avoided (Chamberlain,1981).

2.6.3 Extrusion of Cores From Samplers

Methods of extrusion of permafrost cores from the samplers are not commonly reported in the literature. However, extrusion may cause serious mechanical disturbance of the core, if proper methods are not used.

Although extrusion is often performed under climate controlled conditions in the laboratory, most published accounts deal with extrusion of the cores at the drilling site. Cass (1959) found the frozen soils removed by hammering were seriously fractured to the point where meaningful lab tests were no longer possible. Davis and Kitze (1967) made use of a field-fabricated extruder with a level-operated ram, but found the extrusion of small-diameter samples difficult. Roggensack (1979) preferred extrusion with a hydraulic ram over vibratory extrusion from core barrels which was found to cause significant mechanical disturbance, mainly in the form of cracking of ice lenses.

2.6.4 Field Description and Classification of Permafrost Cores

As cores are extruded from the samplers, a quick description and classification of the sample should be made. Because of time constraints, it should only be necessary to identify major stratifications and ice lens thicknesses at this time. The limits of permafrost zones in the soil should be identified at this time. Mobile Augers (1978) suggests that the core be colour-photographed at this time, so that detailed descriptions may be made later outside cold

storage facilities. It is recommended that photographs of test pit walls and all frozen cores and samples be taken for a permanent record (Johnston, 1981). Cores should be examined in detail under climate controlled conditions in the laboratory.

2.6.5 Core Handling and Storage at the Drilling Site

During photographing of cores after extrusion, the length of exposure to atmospheric conditions should be kept to a minimum, particularly when the air temperature is near or above freezing. After field examination, the core is wrapped in cellophane and placed in a doubled polyethylene bag or a PVC core container (Savigny,1980). In either case, it is important to evacuate the air from the container to avoid moisture loss due to evaporation and sublimation. It is advisable to wrap the containers in corrugated cardboard for transport.

Since drilling sites are often remote, refrigeration facilities are not always readily available, and measures must be taken to temporarily store the core on the site. In winter, cores may be placed under snow cover to provide a moist environment shaded from sunlight. In warm weather, cores may be stored in covered, insulated pits. Veillette and Nixon (1980), report that cores have been stored below the frost line in specially bored and capped storage holes, forming a sort of natural refrigerator. Insulated storage boxes (see Fig.2.3) of the type used by the University of Alberta (Savigny,1980) have been used successfully to store permafrost cores for up to 9 hours in warm weather with no apparent deterioration (Baker,1976). Snow, ice cubes, or dry ice may be used as a refrigerant in the box, however, samples should be insulated from dry ice to avoid "burning" effects.

2.6.6 Transportation of Samples to Laboratory

After packing, permafrost samples should be moved as quickly as possible to permanent temperature and humidity controlled storage facilities. Samples should be wrapped with corrugated cardboard, or a similar material, to minimize mechanical disturbance. Baker (1976) suggests that a "competent" person should accompany the samples on their journey to the laboratory to ensure proper handling.

2.6.7 Field Laboratories

Where drilling projects are large enough to warrant their use, field laboratory facilities are a valuable asset. Ladanyi (personal communication) recommends that as much testing as possible be performed in a field lab. Even the most sophisticated triaxial creep tests may be performed in properly-equipped field laboratories. Lawrence (1971) reports that many procedures, such as grain size distributions, Atterberg limits, carbonate and moisture contents, specific gravity, bulk density, unfrozen water contents, and the trimming of fluid-contaminated samples have been performed in field laboratories operated by GSC. The use of field laboratories can reduce transportation and storage problems.

2.7 SUB-SAMPLING OF PERMAFROST CORES AND SAMPLE PREPARATION PROCEDURES USED AT CRREL

CRREL favours sub-sampling in the laboratory of larger samples taken from the field (Sellmann, private communication). This is a procedure whereby a plug is cored from a larger core or from a large block sample. Typically, a sub sample would be two inches in diameter. CRREL uses miniature core barrels driven by an ordinary drill, and equipped with

tungsten carbide bits. Air is used as the circulating fluid. A fluted system may also be used.

Holes may be drilled into sub-samples for special testing purposes, for example, the placement of thermistors for thermal conductivity measurements.

The same equipment that is used for rock testing purposes is adaptable to sample preparation for permafrost. Trueness of the end and bonding of the end caps are key considerations (Mellor and Chamberlain, private communication). Forming tools have been made for sample preparation and lathe trimming is used. Samples are first machined to the desired diameter on a lathe. Then the machine sample is clamped in a special jig (see Fig.2.4) and run against an end facing tool mounted in the lathe chuck. Several measurements of specimen length are made and recorded.

TABLE 2.1 Permafrost Sample Classification
(modified from Idel et al, (date unknown)

CLASS		CORE DESCRIPTION	APPLICABLE TESTING
1	VH	undisturbed core, held at in situ temperature	mechanical strength and stiffness (frozen state) behaviour during thaw
2	H	undisturbed core, allowed to thaw (temperature change in storage or transport)	mechanical strength, stiffness (thawed), liquefaction potential permeability, behaviour during freezing
3	MH	slightly disturbed core	in situ density, porosity, void ratio
4	M	moderately disturbed core	moisture content, fine stratification
5	ML	largely disturbed core	major stratification, grain size, Atterberg limits, specific gravity, organic matter
6	L	cuttings	sequence of strata

TABLE 2.2 Relationship Between Sample Quality and Drilling/Sampling Method for Various Frozen Materials

SAMPLE QUALITY CLASS	SAMPLE DESCRIPTION	APPLICABLE DRIVING SAMPLING METHOD	MATERIALS SUITED FOR SAMPLING
1	undisturbed, to slightly undisturbed continuous core	rotary drilling with core barrel samplers, double and triple tube swivel types (also wireline core barrels)	-cold temperature frozen soils -frozen coarse gravels -soils with significant cobbles and boulders -rock
		augering with CRREL barrel	-fine grained soils -organic soils -ice, snow (no cobbles, boulders)
2, 3	moderately disturbed sample	vibratory drilling with split and solid tube samples	-frozen and unfrozen fine grained soils
		drive samples with split or Shelby tubes	-frozen fine grained soils -partially frozen peats, clays
4	highly disturbed samples	rotary drilling with single and double rigid tub core barrel samplers	-cold temperature frozen soils -frozen coarse grained soils -cobbles, boulders
		drive sampling -solid or split tubes	-frozen coarse grained silts
5	completely disturbed and remoulded samples and bulk samples	augering -chips, cuttings	-fine grained soils
		drive sampling -solid or split tube, retrieve sample with 'core catcher'	-coarse grained soils

TABLE 2.3 Summary of Drilling and Sampling Techniques Used in Frozen Soil

METHOD OF DRILLING	SAMPLING TECHNIQUE	SAMPLE SIZE (diameter)	MATERIAL SUITED FOR SAMPLING	SAMPLE QUALITY[1]	ADDITIONAL COMMENTS
percussion	drive sampling: -split tubes -Shelby tubes	7.5 cm	frozen fine grained, partially unfrozen clays, peats	3-M	-samples are largely mechanically disturbed -not recommended for hard soils, rock, soils with frequent cobbles, boulders and cold temperature frozen soils
augering	chips, cuttings	chips	fine grained soils, organic soils, ice, snow	5-L	-good only for sequence and type of strata
	CRREL ice-coring auger	7-11 cm		1-H/VH	-must operate at low rpm -often jams on cuttings -lightweight, portable, can be hand operated at shallow depths
vibratory	solid and split tubes		fine grained frozen and unfrozen soils	1/2-H	-sampler advanced by vibrating drill and liquefying adjacent soil particles -long cores are possible -high penetration rate -not good if rocks, cobbles present or for gravel cores -easy removal of jammed tubes

[1] See Table 2.2

TABLE 2.3 (CONT'D)

METHOD OF DRILLING	SAMPLING TECHNIQUE	SAMPLE SIZE (diameter)	MATERIAL SUTED FOR SAMPLING	SAMPLE QUALITY	ADDITIONAL COMMENTS
rotary	core barrel: -single tube	7-15 cm	compact rock, frozen peat	4-M/L	-core-largely disturbed -often eroded by drill fluid -useful where core recovery is secondary (starting drill hole)
	-double tube (rigid type)	2.5-7.5 cm	compactor slightly fractured rock	4-M/L	-core-very disturbed (mechanically) -less erosion, contamination than for single tube
	-double tube (swivel type)	2.5-5.5 cm	.cold temperature frozen soils coarse frozen gravels cobbles, boulders, rocks	1-H/VH	-inner tube stationary -protects core from large mechanical disturbance -inner tube adjustable so t minimize surface contamination of core -not recommended for partially frozen and unfrozen soils
	-triple tube (swivel type)	2.5-5 cm		1-H/VH	-as for double tube (swivel) but with split tube casing inside -easier handling of core at surface
	wireline core barrel -double and triple tube (swivel type)	2.5-6 cm		1-H/VH	-as for double tube (swivel) -inner tube may be retracted to surface -lessens thermal disturbance -practical for large depths

TABLE 2.4 Standard Core Barrel Designs, and Bit Dimensions (A), and Boyles Nonstandard WL Wireline Series (B) (after Veillette and Nixon, 1980)

A

CORE BARREL DESIGN				CORE BIT					
WF	WG*	WM	WT	O.D. set (inches)	I.D. set (inches)	Kerf width (inches)	Hole diameter (inches)	Core diameter (inches)	Core-to-hole ratio (area)
			RWT**	1.160	0.735	0.220	1-3/16	23/32	39.1%
	EWG	EWM		1.470	0.845	0.320	1-1/2	13/16	32.4%
			EWT	1.470	0.905	0.290	1-1/2	7/8	37.1%
	AWG	AWM		1.875	1.185	0.352	1-15/16	1-3/16	39.3%
			AWT	1.875	1.281	0.304	1-15/16	1-9/32	45.9%
	BWG	BWM		2.345	1.655	0.352	2-3/8	1-5/8	49.1%
			BWT	2.345	1.750	0.305	2-3/8	1-3/4	55.0%
	NWG	NWM		2.965	2.155	0.412	3	2-1/8	52.2%
			NWT	2.965	2.313	0.333	3	2-5/16	60.2%
HWF	HWG			3.890	3.000	0.453	3-15/16	3	59.0%
			HWT		3.187	0.360	3-15/16	3-3/16	66.5%
PWF				4.725	3.627	0.560	4-3/4	3-5/8	58.4%
SWF				5.725	4.439	0.654	5-3/4	3-7/16	59.7%
VWF				6.840	5.505	0.682	6-7/8	5-1/2	64.2%
ZWF				7.840	6.505	0.682	7-7/8	6-1/2	68.3%

*Formerly X series
**Formerly XRT
Adapted from Canadian Standards Association (1972)

B

Core barrel design WL	O.D. set (inches)	I.D. set (inches)	Hole diameter (inches)	Core diameter (inches)	Core-to-hole ratio (area)
AWL	1.875	1.062	1-15/16	1-1/16	30.2%
BWL	2.345	1.433	2-3/8	1-7/16	33.7%
NWL	2.965	1.875	3	1-7/8	39.1%
HWL	3.762	2.500	3-51/64	2-1/2	43.4%

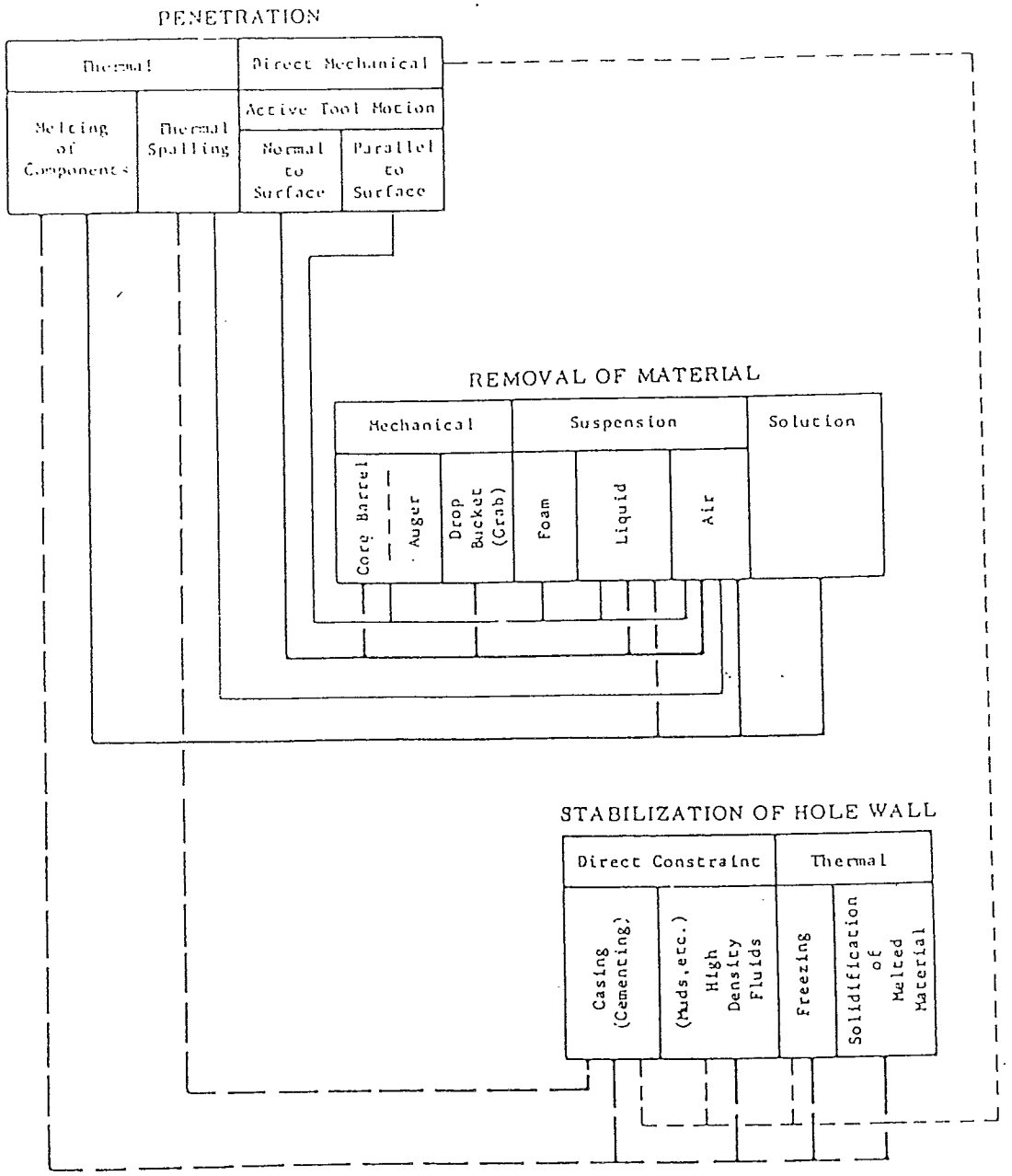

FIGURE 2.1 Elements of Practical Drilling Systems and Suggested Compatibility Links. (after Mellor and Sellmann, 1975)

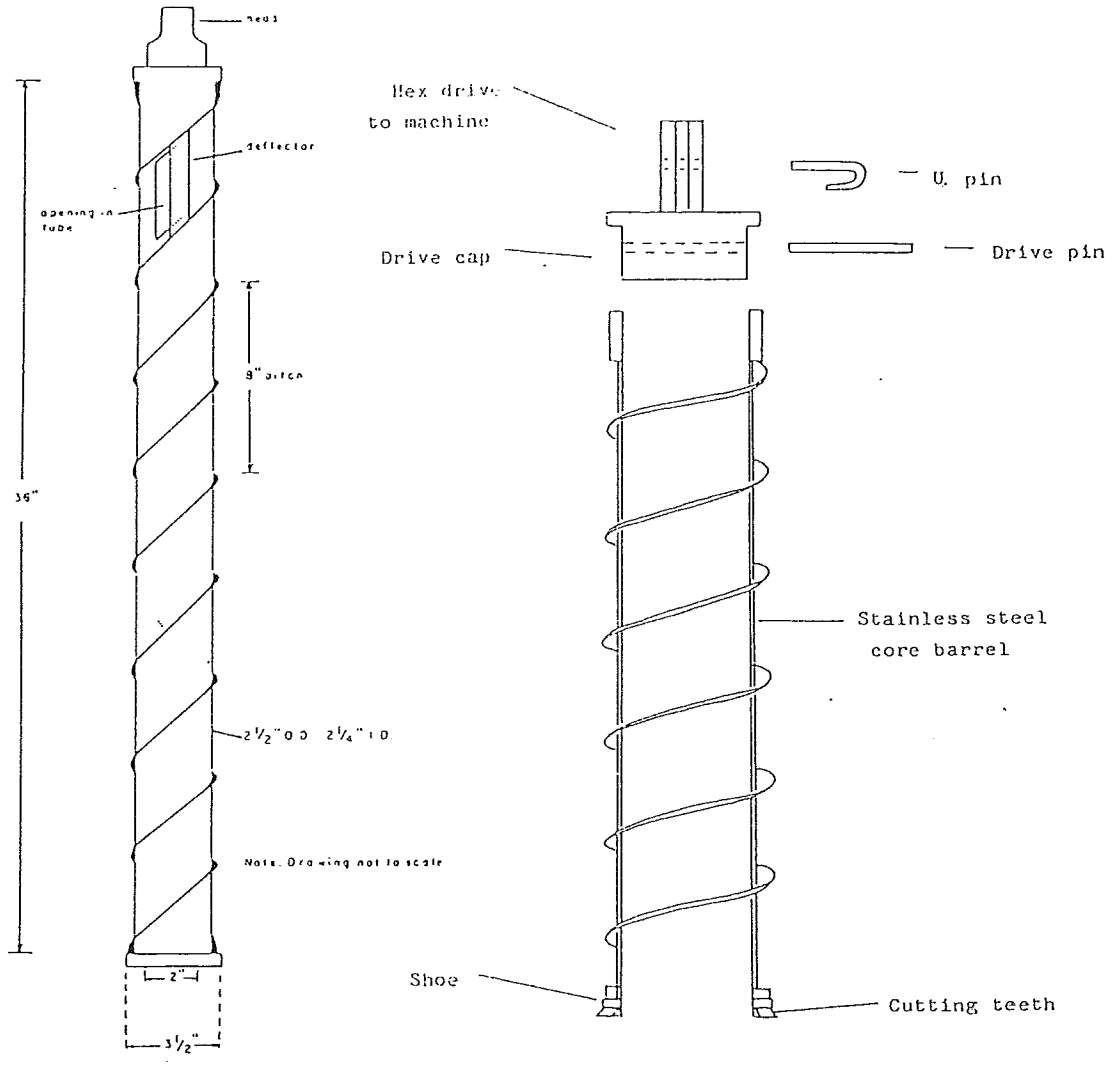

FIGURE 2.2 Modifications of CRREL Ice-Coring Auger used in Canada

(a) GSC (Veillette, 1975)
(b) Mobile Augers (1978)

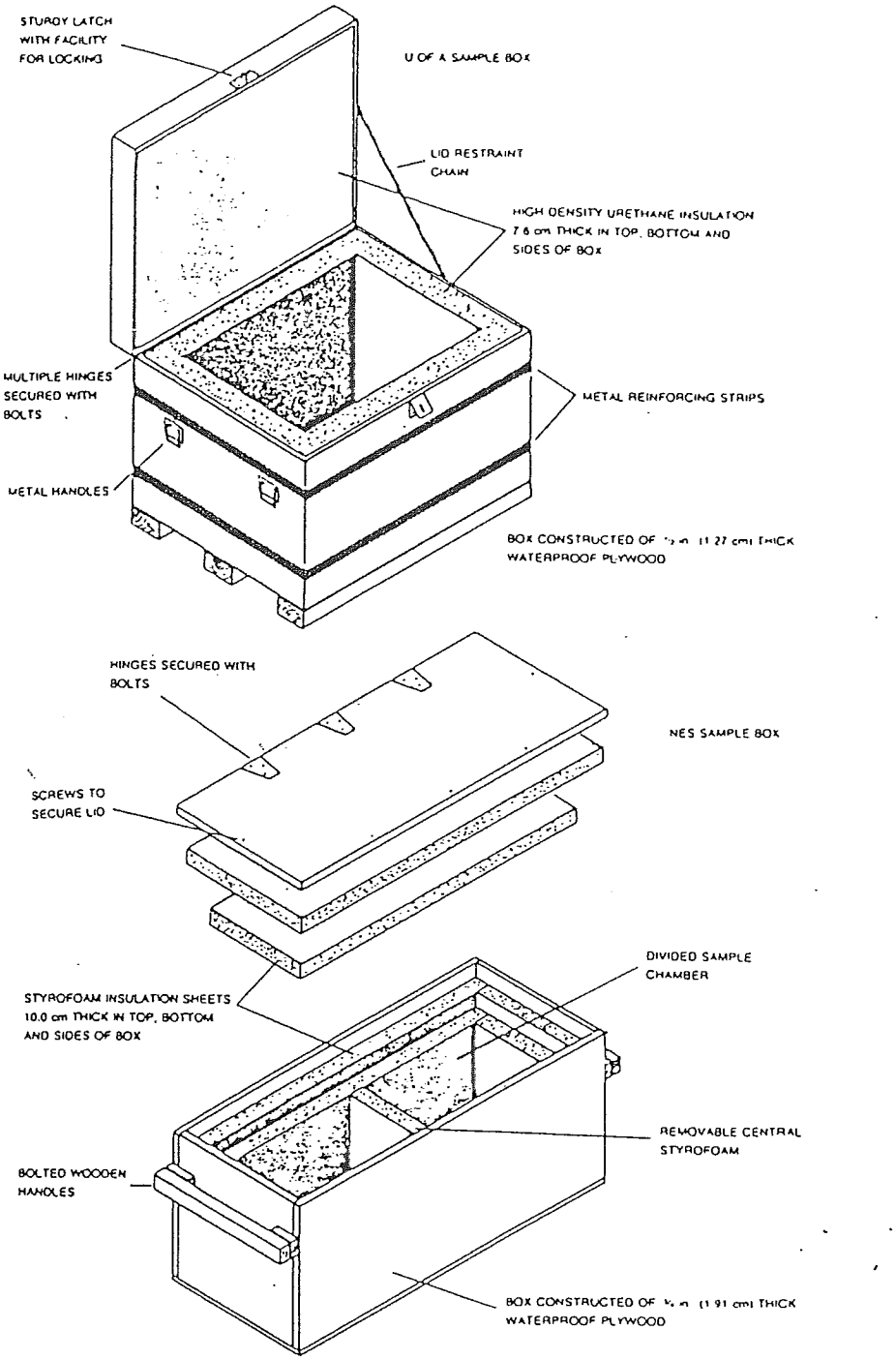

FIGURE 2.3 Types of Boxes Used to Store and Transport Undisturbed Frozen Cores (after Savigny, 1980)

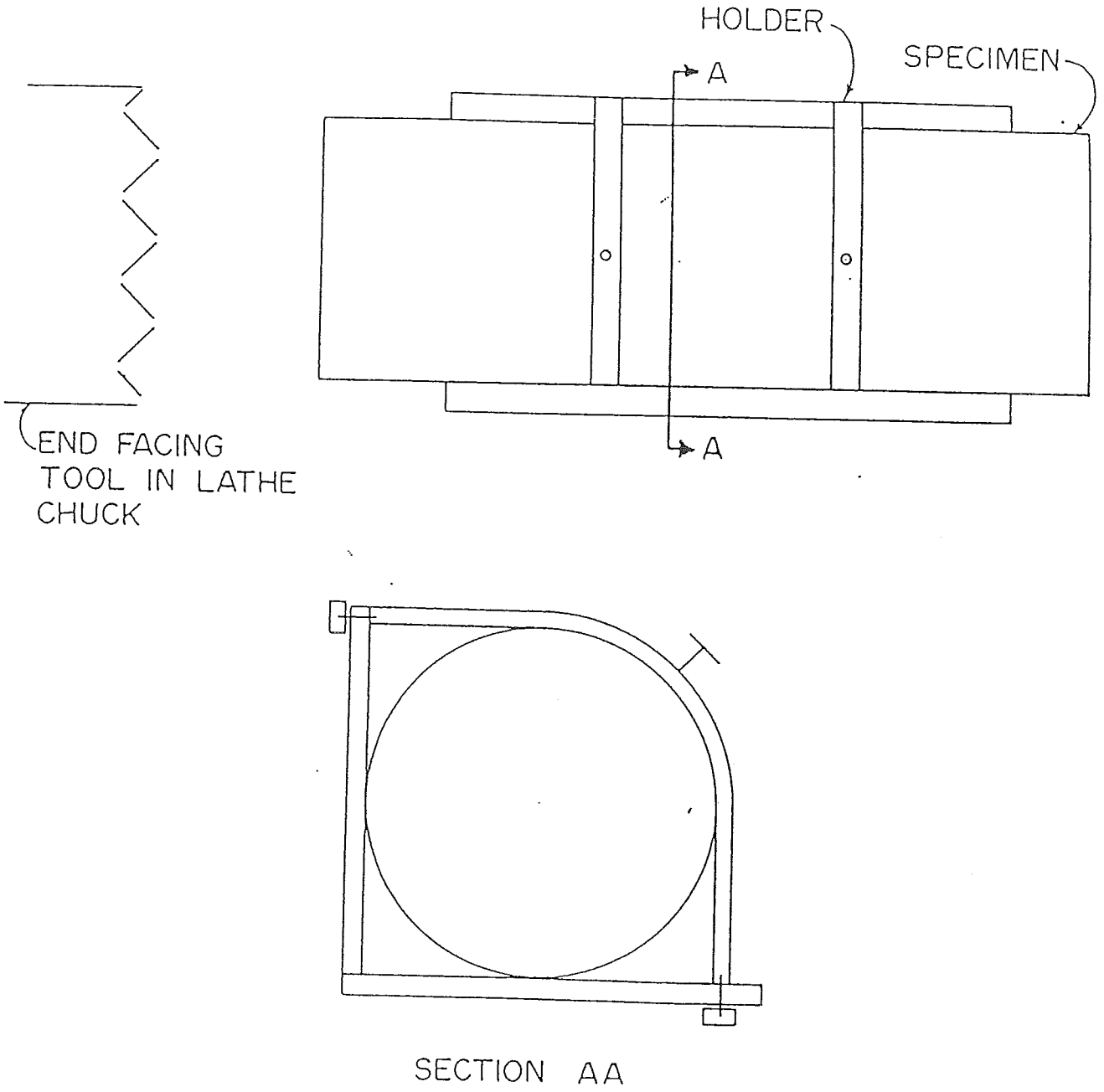

FIGURE 2.4 Clamping Device for End Facing Specimens (Sellman, private communication)

3. TESTING OF PERMAFROST CORES AND SAMPLES

3.1 GENERAL

In permafrost terrain earth materials in a frozen, freezing, thawing, thawed and unfrozen state may be expected on most engineering projects. The properties and behaviour of such complex materials under load will be more varied than in nonpermafrost areas, even though their composition and moisture content may be similar. Laboratory tests under controlled conditions, may be used to anticipate material properties and behaviour when engineering projects are undertaken.

The various types of laboratory tests are described in the following Sections. The Sections are generally subdivided according to the various agencies, companies, etc. who perform those particular tests and who have published test procedures and descriptions of their apparatus. Where there are several publications on one test type from one organization, the most complete test procedure and/or apparatus description has been used. Most of the published data deals with testing on man-made rather than natural permafrost. Test procedures and apparatus have been included irrespective of the origin of samples being tested.

3.2 CLASSIFICATION AND INDEX TESTS

3.2.1 General Classification and Description

3.2.1.1 Classification

Many of the standard classification procedures and index tests for unfrozen soils (see Section 3.2.4) also apply to frozen soils. An additional series of tests may be performed in order to more thoroughly classify frozen soils.

A full description of a frozen soil must include those characteristics which are the most significant indicators of engineering behaviour, i.e. soil type, ice content and distribution, and temperature (Frost Effects Laboratory,1952).

An extension of the Unified Soil Classification System (U.S.Army Corps of Engineers,1953) to describe frozen soils was proposed by Linell and Kaplar (1963). In this system, the soil phase of the frozen sample is described by the USCS method. This description is augmented by a description of composite ice-soil structure, if the ice is less than 25 mm in thickness, or if the ice itself is greater than 25 mm in thickness. The nomenclature for this method is described in Table 3.2.1.

The above classification system includes guidelines for describing the ice phase, with respect to hardness, structure, colour, and admixtures. Savigny (1980) noted that the description of the ice structure and distribution in core samples of frozen soils often differed from that in-situ, as based on the Linell and Kaplar system. Savigny proposed that a description of ice-soil structure as seen in the field (pore ice, segregated ice, reticulate ice, and stratified ice) should accompany any classification of frozen core samples.

Frozen soils may also be classified with respect to their freeze-thaw behaviour which is primarily governed by the total moisture content. Ziwang (1979) classified frozen soils into degrees of thaw settlement probability (see Table 3.2.2).

3.2.1.2 Ice Structure

Often it is necessary to study the structure of ice in frozen soil core samples. A common method of studying ice structure is by microscopically examining sections of frozen cores. Osterkamp (1975) makes recommendations with regard to the preparation of these samples. A diamond-wire saw, similar to that used for cutting semiconductor elements for micro-electronics applications, is modified to cut thin sections of frozen soil cores. Since it is beneficial to avoid thermal disturbance of the cores, cutting should take place in a climate-controlled cold room, and the saw should be lubricated with low-temperature lubricants. Sections should be cut to 0.4 - 0.5 mm in thickness. Wire speeds of 10 - 30 cm/s with a cutting force of 20 - 100 g are recommended to produce smooth surfaces within a reasonable time. Wire diameters of 0.34 mm are advised, with wire tension as recommended by the manufacturer. A lubricant should be applied to the cut surface at a rate of several drips per minute (this requires regular cleaning of the saw pulleys). After sawing, sample sections should be cleaned by a tissue. Sections may be stored by mounting between projector slide covers, sealing the edges and placing in a tightly-sealed plastic bag, and storing at -25^{o}C.

There are several methods of viewing core sections under a microscope. Osterkamp (1975) studied ice structures of frozen soil core sections by microscope, photographing them in ordinary and polarized light. Zigert (1973) used the dark-field method in which light is directed at the sample at such an angle so that it is not reflected back to the micro-

scopic objective. (Ice tends to melt or sublimate in direct light.) This gives a clear-coloured image in which the internal structure of poorly-reflecting minerals may be studied. Zigert also describes the "replica" method, in which polymeric solutions are used to make an impression of the surface of a specimen which may then be studied at room temperature and stored for indefinite periods with no temperature effects. Polymers which are soluble in dichloroethane are best suited for replicas since they do not dissolve ice. After casting, minerals should be washed from the surface of the casting with hydrofluoric acid.

Sinha (1977) gives the following procedure for the replication of ice surfaces for the purpose of examining the ice microstructure.

Preparation of the Surface

Thick sections (up to 2 cm) of required orientations were cut with a band saw. Each was mounted on a clear glass plate by freezing a few drips of water at the edge, making certain that no water entered the space between the glass and the specimen. The latter condition can be obtained by using water precooled to just above 0°C. The exposed surface of the section was then microtomed to a mirror finish in three stages. First 1500 μ (1.5mm) was removed from the surface, 10μ at a time. This was followed by removal of the next 500μ in 5μ layers, ensuring that the blade was clean before each pass. The quality of the surface was examined visually, using reflected light from a distant source, and also with an optical microscope. This procedure was used to prepare surface areas up to 8 x 12 cm with a mirror finish. On several occasions both surfaces were finished in this way to provide a thin section 0.4 mm thick for analysis with transmitted polarized light. In these cases the initial thickness was 5 mm. After preparing the first surface, a specimen was removed from the glass plate by careful cutting of the bonding ice with a sharp razor blade. It was then remounted on another clean glass plate with the prepared surfaces facing the glass, and microtomed until the second surface had a mirror finish.

Replicating Procedure

A freshly prepared specimen was kept in a horizontal position inside a transparent plastic or glass box containing crushed ice. The vapour pressure inside the box was controlled qualitatively by varying the degree of closure of the top of the box and providing a gentle flow of air around the box. Transparency of the box allowed the specimen to be observed externally without disturbing the controlled conditions of temperature and humidity inside. A 5% solution of FORMVAR (polyvinyl formal) in ethylene dichloride was placed slowly on the freshly prepared ice surface with an eye-dropper to a thickness of about 0.5 mm. The solution was allowed to dry on the ice surface while the specimen remained in the controlled environment of the box. The drying time lasted about 2 to 3 minutes.

Replicas were removed by peeling, melting the ice in water and allowing the film to float, and sublimating the ice, the method being determined by the particular experiment under consideration. They were carefully mounted on large glass slides with the replicated surfaces facing upwards and observed through an optical microscope. Selected areas were prepared for examnination with a scanning electron microscope by vacuum deposition of a layer of carbon followed by a plating of gold.

3.2.1.3 Organic Content

The determination of organic content is commonly made by means of the ignition test. In this test, mineral and organic solids are separated by destruction of the organic content. A standard procedure for measuring the "Moisture, Ash, and Organic Matter of Peat Materials" is given by ASTM (D2974). High temperatures are needed for the combustion of organic material. This causes errors due to the loss of surface hydration water from the mineral component, and incomplete decomposition of the organic matter.

Al Khafaji and Andersland (1981) used the following procedure to measure the organic content by the ignition test and to develop a correction factor for the sources of error mentioned above.

Sample Preparation

Freeze-dried pulp fiberboard was separated into a fluffy mass. Selected proportions of dry kaolinite and dry fiber were mixed. Next, distilled water was added in amounts needed to form a slurry. Nutrients and seed microorganisms, in predetermined proportions, were added directly to the clay-fiber slurry to help accelerate anaerobic decomposition of slelected laboratory samples. Nitrogen served as the base by which other nutrient quantities were computed. Approximate ratios giving optimal decomposition rates included C/N = 30:1, P/N$\simeq$1.5, and (Mg, Fe, K, Ca, and Na)/N$\simeq$1:16. Pulp fiber supplied carbon, NH_4Cl supplied nitrogen, K_2HPO_4 for phosphorous and potassium, $MgSO_4$ for magnesium, $CaCl_2$ for calcium, and $FeCl_3$ for iron. About 1% (dry-weight basis) of municipal sludge provided seed microorganisms.

Decomposition Photos

The extent of microbial attack on pulp fibers was observed using a scanning electron microscope. Details for sample preparation and mounting of samples on small aluminum stubs are given by Al-Khafaji. A pulp fiber with no decomposition, has holes with dimensions ranging from about 2μm up to 15μm. An advanced stage of decomposition, indicates a general breakdown of the fiber's structural integrity. The ability of microorganisms to maintain high concentrations in small cavities may have accelerated the process at certain locations. Colonies of rod shaped bacteria are visible on the fiber surface. These photographs help one visualize changes in the fibrous organic material due to decomposition.

Ignition Test

Soil organic material is combustible whereas the mineral constituent is incombustible and ash forming. Separation of the two soil components was accomplished by firing an oven-dried (105°C) sample in a muffle furnace at specified temperatures until the organic material was reduced to an ash. Test equipment included a platinum crucible with lid, an analytical balance having a sensitivity of 0.1 mg, and an electric muffle furnace capable of

maintaining selected temperatures within ±25°C. Weight-reduction curves for the materials, pulp fiber and kaolinite, were determined using temperatures ranging from 200°C to 900°C with oven-dried fiber sample sizes sufficient to yield minimum ash (or residue) weights of 10 mg - 20 mg. For samples containing mineral fractions, oven-dry weights up to 10 g were used. After ignition and some cooling, the crucible with sample and lid was placed in a desiccator. When cooled to room temperature the weight was determined. The ash (or residue) fraction was determined from the equation

$$X_m = \frac{\text{weight of ash or residue}}{\text{oven dry sample weight}}$$

The organic fraction X_f, without corrections, was taken to be $(1 - X_m)$. A correction for loss of surface hydration water from the mineral fraction is developed in a later section. Organic fractions for the decomposing model soils were obtained in the same manner using small oven-dry samples.

3.2.2 Water Content

3.2.2.1 Bulk Moisture Content

The bulk (total) moisture of a frozen soil sample may be determined by the standard procedure ASTM D2216 "Standard Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures."

Alternate methods of finding the bulk moisture content are included in the procedures for determining the unfrozen portion of the moisture, and are outlined in part of this section.

The volumetric quantity of ice in a sample of segregated ice has been traditionally estimated visually from the proportion of ice observed in the overall surface area of a permafrost sample. This method is prone

to errors caused by individual procedures and lack of precision (Savigny,1977).

A more precise procedure for estimating the volumetric ice content is described by Savigny (1977). Microdensitometers are used to precisely determine the ice content on the basis of surface area. A representative portion of exposed segregated ice is photographed. The photograph (or transparency) is viewed on a screen and divided into ice and soil segments by scanning gray tones and brightness levels of each with the multi-density slicer. Each density level is superimposed over the monitor image until both segments are accurately outlined. The area of each segment is determined automatically by the analyzer, as a percentage of the total viewed area. The level of accuracy is dependent on the quality of the photographed surface. Samples should be scraped and washed with a small quantity of water before photographing. The area studied should be representative of the sample. High density (low speed) film should be used with a flash or other controlled light source. Photographs taken for the determination of the volumetric ice content (I) provide a useful supplement to the core-logs.

The bulk moisture content may be estimated from:

$$W_b = \frac{90I + G_s\,(W_n\,(100 - n_a))}{G_s\,(100 - I - n_a)} \qquad \text{(Savigny, 1977)}$$

where: W_b = bulk moisture content (%)

W_n = moisture content of the soil component of segregated ice

I = volumetric ice content (%) as described above

n_a = air porosity (%)

G_s = specific gravity of the soil particles

The soil moisture content and specific gravity may be found from standard tests on a sample of the core taken during the bulk moisture test. The air porosity of a permafrost core is generally less than 5% (Roggensack,1977). The above relationship is presented graphically in Fig.3.2.1.

Correlations between the results of this method and direct bulk moisture determinations are quite good.

3.2.2.2 Unfrozen Water Content

A significant amount of unfrozen water may exist in frozen soils, even at low temperatures. This water acts to separate ice from the mineral grains, as evidenced by measurement of ionic diffusion through frozen soils. The presence of unfrozen water has significant effects on soil properties such as strength and hydraulic and thermal properties.

The unfrozen water content of a frozen soil is dependent on a number of factors, the most important of which is temperature. In clayey soils, the amount of unfrozen water decreases severely as the soil is cooled from $0^{o}C$ to about $-5^{o}C$, as ice forms in the soil voids. Below $-5^{o}C$ there is little change in the unfrozen water content. Other factors which influence the amount of unfrozen water are pressure, specific surface area of the soil, the chemical and mineralogical composition of the soil and pore water, and other physiochemical properties, such as cation exchange capacity. The unfrozen water content, W_u, has been found to be independent of the rate of freezing (Williams,1964), but not of the freezing history of the soil. Different unfrozen water contents will be measured if a certain temperature is reached by cooling or warming (Williams,1964; Leonards

and Andersland,1960). The value of W_u will also vary between the first and subsequent freeze-thaw cycles (Williams,1964).

Anderson and Morgenstern (1973) reviewed the various methods of measurement of unfrozen water content. These methods are described in the following paragraphs.

a) Dilatometry

One of the oldest methods is dilatometry (Bouyoucos,1917), in which the volume changes of a soil slurry with a known moisture content are measured during freezing in order to determine the relative proportions of ice and water. This method assumes the pore fluid is immiscible and remains completely inert when it moves in the soil voids, and that soil water expands as much as pure water during freezing. These assumptions can cause large errors in estimating the unfrozen water content.

A temperature and pressure controlled dilatometer has been developed at Carleton University. The dilatometer is used for the accurate determination of the change in the volume of freezing soils, or any other material, under either isothermal or isobaric conditions. The apparatus and procedure are described below (El Khoraibi,1974a).

Apparatus

The cell. It consists of a stainless steel cylinder - 2.2 in. inner diameter, 4 in. outer diameter, and 4 in. in height - together with two stainless steel end plates, see Fig.3.2.2. The lower end plate has a drainage port. Two thermoelectric heat pumps (Peltier modules) are attached to the two end plates for cooling the cell, from top and bottom, to the desired temperature. The power supply to these modules is controlled by a thermoelectric cooling control unit* so that the cell temperature can be maintained constant for suitable periods of time. Nine thermistors are fixed to the wall of the cell at various points to determine the average cell temperature and to check the uni-

*For more information refer to: "Thermoelectric Cooling for Precise Temperature Control of Frozen and Unfrozen Soils", by P.J.Williams, Canadian Geotech.J., Vol.V, No.4, Nov.1966, pp.264-266. The Unit is obtainable from Intertechnology Limited, Don Mills,Ont.,Box 219.

formity of temperature throughout the cell. Another two thermistors are fixed to the two end plates to determine their temperature and thus to adjust their temperature to the desired value, by adjusting the thermoelectric cooling control unit settings.

The cell is connected to the volume measuring assembly through a stainless steel tube. It is also connected to the mercury reservoir through a stainless steel valve (valve no.4), see Fig.3.2.3.

The volume measuring assembly. This consists of two pipette tubes, 10 ml and 1.0 ml, see Fig.3.2.3. The two tubes are connected to each other and to the cell by means of stainless steel tubes. A set of valves (valves no.1,2,3) are arranged in such a manner as to allow for the flow of mercury from one pipette tube to the other and from one pipette tube or both to the cell and vice versa. The 1.0 ml pipette tube is used for the accurate determination of the displacement of the mercury level inside the pipette resulting from the change in volume of the mercury inside the cell. The 10.0 ml pipette serves as a reservoir for the flow of mercury to or from the 1.0 ml pipette. It may be used, however, as a rough estimate of the change in volume of mercury inside the cell. The top end of each pipette is connected, through a stainless steel valve (valves 5 and 6) to a nitrogen supply under pressure. The desired pressure is applied as a gas pressure at the top of the 1.0 m. pipette through the mercury, to the soil sample inside the cell. Each pipette tube is located inside a glass cylinder filled with silicon oil. The bursting pressure against the wall of the pipette is reduced by applying gas pressure to the oil inside the glass cylinder. Furthermore, the oil and the glass cylinder provide a safeguard against the explosion of the pipette when high pressure is applied.

Control of Cell Temperatures

The temperature throughout the cell should be maintained uniform, and kept constant during the experiment. This is accomplished by wrapping the cell in an insulating material (foam rubber), and by placing it inside an insulated box, see Fig.3.2.3. The air temperature in the box is brought down to a temperature 3.5°C lower than the cell temperature, by circulating a liquid (methyl-alcohol), at a controlled constant temperature, through a coil of copper tubing placed adjacent to the inside walls of the box. To check the stability of cell temperature over a period of time, a thermistor is fixed to the wall of the cell at its mid-height. The thermistor's signals are amplified

and recorded on a recorder. Any change in cell temperature is thus recorded during the experiment.

Setting the Dilatometer for Testing

For the accurate determination of the change in volume of the frozen soil on freezing and/or applying pressure, the mercury must completely fill the space between the soil sample, contained inside the rubber membrane, and the wall of the cell. This is accomplished by the following procedure:

1) Fit the rubber membrane into the cell in such a manner that enough space is provided for the expansion of the soil sample.

2) Place the soil sample into the rubber membrane until the rubber membrane is filled as shown in Fig. 3.2.3.

3) Immerse a millipore membrane filter (pore size 0.2μ) in boiling water until its pores are saturated.

4) Place the membrane filter on the surface of the soil sample.

5) Mount the end plate in place. Care must be taken when placing the end plate so that no air bubbles are trapped between the inside surface of the end plate and the soil sample. The bolts are tightened by means of a torque wrench (applied torque 10 ft.lb.).

6) Mount the other end plate in place.

7) The outside surface of the cell is completely covered with one layer of foam rubber 3/4" thick. Place the cell inside the insulated box.

8) Connect the cell to the volume measuring assembly and the mercury reservoir.

9) Open the valve leading to the mercury reservoir. Also open the valves of the volume measuring assembly. The mercury is allowed to flow into the cell at a slow rate, and to rise inside the pipettes to the desired level. Close the valve leading to the mercury reservoir.

10) The soil sample is allowed to consolidate under the weight of the mercury and the excess soil water drains through the drainage port.

11) Wait until the mercury level in the pipettes ceases to change, i.e., the consolidation process is completed. The drainage port is sealed off.

*12) Close the valve leading to the 10 ml pipette.

13) Record the initial mercury level in the 1.0 ml pipette.

14) Apply pressure to the cell at the top of the 1.0 ml pipette. The applied pressure is increased in steps and the corresponding mercury level in the 1.0 ml pipette is recorded in each increment. This is continued until the highest pressure to be applied in the course of the experiment, is reached. Release the applied pressure.

15) Disconnect the cell and the mercury reservoir.

Test Procedure

1) Open the valve leading to the 10 ml pipette. Record the mercury level in both pipettes. Close the valve leading to the 10 ml pipette.

2) Record the thermistor readings at room temperature.

3) Connect the cooling water line to the heat sinks and the water is allowed to flow.

4) Connect the thermoelectric heat pump power leads to the thermoelectric cooling control unit. The thermistor leads are plugged in.

5) Apply the desired pressure to the soil sample at the top of both pipettes.

6) Switch on the thermoelectric cooling control unit, and adjust the settings to give the desired cooling temperature at the two end plates. The two end plate thermistors' readings will indicate when the desired cooling temperaturee has been reached.

7) Allow the methanol to flow through the copper coil. Adjust its temperature to bring down the air temperature inside the insulated box to the desired temperature.

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* Steps 12 to 14 are carried out to investigate the presence of air bubbles inside the cell, i.e. when the soil sample is virtually incompressible. In case of a compressible soil (partly saturated soil), proceed directly to step no.15.

8) Check the temperature of the two end plates and readjust it to the desired cooling temperature by readjusting the thermoelectric cooling control unit settings.

9) Switch on the recording equipment for recording the variation in cell temperature.

10) Leave the whole assembly overnight to allow the soil sample to cool to the desired temperature.

11) Observe the mercury level in the 1.0 ml pipette at consecutive intervals of time until it becomes constant. Record the final mercury level.

12) Due to supercooling, the soil water will not freeze at freezing temperature near 0°C. To initiate freezing, the temperature of te lower end plate is lowered substantially, approximately -10°C, until the mercury level in the 1.0 ml pipette starts to rise. The end plate temperature is then set back to its original value.

13) Observe the mercury level in the 1.0 ml pipette which is rising due to the expansion of the soil sample on freezing. At the moment it reaches the top of the pipette, close valve no.3 and open valve no.2, see Fig.3.2.3. Apply additional gas pressure at the top of the 1.0 ml pipette in order to force the mercury to flow into the 10.0 ml pipette until it is brought down to its lowest level in the 1.0 ml pipette. Readjust the gas pressure in the 1.0 ml pipette. Close valve no.2, record the mercury level in the 1.0 ml pipette, and open valve no.3. This procedure is repeated all through the expansion of the soil sample.

14) Observe the mercury level in the 1.0 ml pipette until it ceases to change. Record the mercury level.

15) Check the stability of cell temperature on the recorder. Record the thermistor readings and find the average cell temperature.

16) Adjust the thermoelectric cooling control unit settings to the next cooling temperature and proceed as before.

17) After completion of the experiment, turn off the thermoelectric cooling control unit, the cooling water flow, the

methanol flow, and release the applied pressure. Allow the soil sample to thaw.

18) Wait until the cell temperature is brought up to room temperature. Open the valve leading to the 10 ml pipette and wait for the mercury level in both pipettes to stabilize. Record the mercury level in both pipettes. Compare the mercury level readings to those obtained in step no.1. This is to investigate any mercury leakage that might have taken place in the course of the experiment.

19) Open valve no.4 and collect the mercury into a graduated cylinder for volume determination of the mercury inside the cell. Calculate the volume of the soil sample.

20) Disconnect the cell from the volume measuring assembly and dismount the cell.

21) Place the soil sample in a dish for water content determination if required.

Determination of the Thermal Contraction Characteristic Curve of the Cell

The displacement of the mercury level inside the pipette is not solely attributed to the change in volume of the soil sample inside the cell. Other factors are to be taken into consideration: 1) the thermal contraction or expansion of the mercury filling the cell, 2) the thermal contraction or expansion of the material of the cell, and 3) the thermal contraction or expansion of the air present inside the cell. Factors (1) and (3) can be evaluated once both the volume and the coefficient of thermal contraction are available. To evaluate factor no.(2), the thermal contraction characteristic curve of the cell is to be obtained as follows:

1) Mount the empty cell.

2) Cover the outside surface of the cell with one layer of foam rubber 3/4" thick. Place the cell inside the insulated box.

3) Connect the cell to the volume measuring assembly and the mercury reservoir.

4) Open the valve leading to the mercury reservoir and the valves of the volume measuring assembly. The mercury is allowed to flow into the cell at a slow rate and to rise inside the pipettes to the top reading. Close the valve leading to the mercury reservoir and the valve leading to the 10 ml pipette.

5) Apply pressure to the cell (approximately 10 psi) at the top of the 1.0 ml pipette, to check the presence of air bubbles inside the cell. Record the mercury level. Release the applied pressure.

6) Disconnect the cell and the mercury reservoir.

7) Repeat steps 3, 4, 6, 7, 8, 9.

8) Observe the mercury level in the 1.0 ml pipette at consecutive intervals of time until it ceases to change. Record the final mercury level.

9) Check the stability of cell temperature on the recorder. Record the thermistors' readings and find the average cell temperature.

10) Adjust the thermoelectric cooling control unit settings to the next cooling temperature and proceed as before.

11) After the desired range of temperature has been covered, turn off the thermoelectric cooling control unit, the cooling water flow, and the methanol flow. Allow the cell to warm up to room temperature.

12) Open valve no.4 and collect the mercury into a graduated cylinder for volume determination of mercury inside the cell.

13) Disconnect the cell and the volume measuring assembly and dismount the cell. Make sure that no mercury is left inside the cell.

14) At a certain cooling temperature, the displacement of the mercury level has been obtained. Thus, by calculating the contraction of the mercury at this temperature, the change in the inner volume fo the cell, resulting from the contraction of the walls of the cell, can be obtained. Draw a curve showing the change in the internal volume of the cell as a function of the cooling temperature.

For the purpose of the determination of the unfrozen water content of frozen soils, the soil sample inside the cell must be completely de-aired. Thus, the displacement of the mercury level inside the pipette of the volume-measuring assembly is a direct measurement of the volume increase of the soil liquid due to freezing. The procedure for de-airing the sample is given below (El Khoraibi, 1974b):

De-airing the Soil Sample

1) The soil sample is allowed to dry at room temperature, crushed, and mixed with enough distilled water to bring it to a slurry.

2) Place the soil in a dish.

3) Place the dish inside a desiccator jar.

4) Connect the jar to a vacuum pump and switch on the pump.

5) continue operation of the vacuum pump until the air bubbles cease to come out of the soil.

6) Fit the rubber membrane into the cell in such a manner that enough space inside the cell is provided for the expansion of the soil sample.

7) Place the cell inside the desiccator jar.

8) The jar is placed on an electric shaker which slowly oscillates in a horizontal direction.

9) The soil should be placed inside the rubber membrane in layers. Place the first layer, one inch thick, inside the membrane, switch on the electric shaker and the vacuum pump. Continue operation of the vacuum pump until the air bubbles cease to come out of the soil. Turn off the electric shaker and the vacuum pump.

10) Repeat step N.9 until the rubber membrane is filled with soil.

11) Immerse a millipore membrane filter (pore size 0.2) in boiling water until its pores are saturated.

12) Place the membrane filter on the surface of the soil sample.

13) Mount the end plate. Care must be taken, when placing the end plate, that no air bubbles are trapped between the inside surface of the end plate and the soil sample. The bolts are tightened by means of a torque wrench (applied torque 10 ft.lb.).

14) Mount the other end plate.

15) connect the cell to the volume measuring assembly and the mercury reservoir.

16) Open the valve leading to the mercury reservoir. Also open the valves of the volume measuring assembly. The mercury is allowed to flow into the cell at a slow rate and to rise inside the pipettes to the desired level. Close the valve leading to the 10.0 ml pipette.

17) Record the initial mercury level in the 1.0 ml pipette.

18) Apply pressure to the cell at the top of the 1.0 ml pipette, about 100 psi. Record the corresponding displacement of the mercury level in the pipette. If the displacement is great, more than 0.4 cc, this implies that the soil has not been properly de-aired and more treatment is needed (as described).

19) Open the valve leading to the mercury reservoir and drain the mercury.

20) Disconnect the cell from the mercury reservoir and the volume measuring assembly.

To set the dilatometer for testing, and to run the test, refer to El Khoraibi (1974b).

b) Adiabatic Calorimetry

Adiabatic calorimetry was the most popular method of unfrozen water measurement during the past two decades. The amounts of ice and unfrozen water are deduced from heat measurements made during

freezing/thawing. It is assumed that no other heat-related reactions occur in the test temperature range, that the latent heat of melting ice and the heat capacities of each component of the soil are known exactly. However, these values cannot always be determined accurately and heat energy that is released as melted water is redistributed through the soil mass. Calorimetric measurements compare well with other methods, however, they do not yield any information concerning the distribution or properties of the unfrozen water. Many errors are associated with temperature measurements in the range between 0 and $-1^{o}C$, since the temperature at which ice first appears is required for calculation purposes. The test procedure is lengthy, requiring 3 to 5 days for each freeze/thaw cycle (Williams,1964).

A brief summary of the apparatus, procedure, and calculation for a calorimeter measurement on a frozen soil is given below (Williams 1963).

Calorimetric Investigations

A calorimeter has been constructed which permits measurement of the amount of heat added to or removed from a soil sample to raise or lower its temperature by a given amount. Three thermocouples inserted in the sample measure its temperature, which is continuously recorded. Temperature differences within the sample are normally less than 1/10°C.

During the warming of a sample, a measured heat input is supplied electrically by a coil wound around the holder containing the sample (Fig.3.2.4). It is necessary that there be no significant exchange of heat with the soil sample other than that arising fromthe heating coil. To achieve this, the sample holder is suspended inside a brass container maintained at a temperature almost equal to that of the sample holder. There is thus no significant temperature gradient and negligible exchange of heat between them. The temperature of the brass container is regulated by a heater in the refrigerated ethylene glycol surrounding it. This heater is controlled automatically by a mechanism which operates when a small temperature difference occurs between the brass container and the surface of the sample holder.

From measured values of the time taken for the temperature of the soil to rise a given amount and rate of heat input to the sample, the quantity of heat supplied to cause the temperature rise is calculated. Results of this type are shown, as the specific heat of the soil (i.e. the amount of heat in calories required to raise the temperature of one gram of soil by 1°C) for various negative temperatures.

The specific heats during freezing are obtained in a similar way except that the brass container is held at a temperature lower by a constant amount than that of the sample holder. The heating coil on the sample is not operated. There is then a steady extraction of heat from the holder, the magnitude of which is determined by prior calibration.

Calculation of the Proportion of Ice and Unfrozen Water In the Soil

The calorimeter results can be used to calculate the ice formation taking place in the soil. By deducting amounts corresponding to the specific heat of the mineral components, ice and water present, from the heat involved in a given temperature change, a value for the heat involved in freezing or thawing water during that temperature change is obtained. Assuming the latent heat of freezing to have the same value as that of free water, a figure is obtained for the amount of ice formed or melted.

c) X-Ray Techniques

X-ray diffraction techniques have been used to measure lattice spacings in order to estimate unfrozen water contents (Tice and Oliphant,private communication). The surface area and average lattice spacing of the soil must be known. This method is applicable only to expansive clays, and neglects water which bounds the surfaces of clay minerals. Procedures for the measurement of lattice spacing by X-ray diffraction and surface area by the ethylene glycol retention method are contained in McKeague (1978).

d) Correlation With Index Tests

Several attempts have been made to correlate the unfrozen water content with other index tests. Dillon and Andersland (1966) developed an empirical relationship between the unfrozen water content, temperature, surface area, and activity which gave good agreement with calorimetric measurements.

The above methods have several common shortcomings. They are time-consuming and require expert operators and equipment. Their results are sensitive to a number of variables (especially temperature) and must be calibrated to the soil being tested. None of these methods is applicable to water content measurements on undisturbed cores of frozen soil; each requires an undisturbed and/or artificially frozen sample. Many of the procedures are time consuming, requiring several days for sample preparation and measurement.

Several new methods for the measurement of unfrozen water content have developed during the last decade.

e) Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) (Anderson and Tice,1971) may be used to estimate unfrozen water contents. This is a variation of the procedure for the differential thermal analysis for the determination of soil mineralogy (McKeague,1978). The only major difference between the procedures is the temperature range over which the exothermic output of the sample is measured. Variations in temperature of a soil sample are observed, relative to an inert material. The temperature at which these variations occur are characteristic of the mineralogy of the soil sample. In the determination of unfrozen water content, an exothermic reaction, corresponding to the latent heat of freezing,

appears as ice begins to form. As cooling proceeds, the magnitude of the exotherm is assumed to be proportional to the amount of ice present.

The DSC method is most suited for measurements of unfrozen water content at very low (below -10°C) temperatures. Measurements made by this method are in good agreement with other methods (Anderson and Morgenstern,1973).

Smith-MacGowan et al (1982) have used the following procedure for specific heat measurements with DSC:

> Calorimeter measurements of specific heats have been made with a Perkin-Elmer DSC-2 differential scanning calorimeter, with output recorded on a Perkin-Elmer single-channel multi-range thermal analysis recorder. Aluminum pans supplied by Perkin-Elmer were used, with no evidence of reaction of these (anodized) pans with any of our samples. All pans were sealed after loading. The calorimeter was operated as follows for most experiments: heating rate 10°C/min, range selection 2 mcal/sec, and recorder sensitivity 5 mv for full-scale deflection. The method used, similar to the "scanning method" described by Mraw and Nass (1979), involved comparison measurements of empty pan versus Calorimetry Conference synthetic sapphire and empty pan versus sample of interest, with heat capacity data for sapphire taken from Ginnings and Furukawa (1953). Nitrogen was used as purge gas.
>
> Calorimetric uncertainties with the instrument and procedure described above amount to ± 1 per cent, but the total uncertainties in various specific heats reported here are larger than ±1 percent because of problems with samples, as discussed later.
>
> Specific heat measurements with the differential scanning calorimeter were made in three series, one with maximum temperature 100°C, one with maximum temperature 180°C and one with maximum temperature 300°C. In the latter two cases, calorimetric samples were pre-heated and maintained at the maximum temperature for 15 minutes for removal of volatile material.

A few measurements were made with larger calorimeters that were designed for measurements of heats of reactions, but could be applied to specific heat measurements.

The samples were stored in sealed, plastic-lined drums immediately after they were obtained. They remained at ambient temperature (about 40°F) for about one week. The samples were then frozen and maintained in this state until they were shipped and stored in sealed glass bottles at room temperature. Mineral solids were characterized by particle size; coarse solids (mostly silica) were larger than 325 mesh (44 microns); and fine solids (mostly clay and silt) were smaller than 325 mesh.

f) Nuclear Magnetic Resonance

Nuclear Magnetic Resonance may be used to determine unfrozen water contents because of the difference in absorption bands between ice and unfrozen water. This method is currently used by the CRREL laboratory (Tice and Oliphant,private communication). Wu (1964) assumed that the unfrozen water content of a frozen soil is independent of the ice content at a specific temperature. The total water content at which the wide ice adsorption band was observed at a specific temperature could then be taken as equal to the unfrozen water content at that temperature.

Wu's assumptions do not apply for all soils. The CRREL laboratory has developed an alternate procedure for nuclear magnetic resonance, based on the assumption that the total water content of a soil will not change with temperature. Small, relatively inexpensive pulsed NMR units are now available. These units apply a series of pulses of radiation to a sample. The amplitude of the signal measured from the first pulse is assumed to be proportional to the unfrozen water content.

The most recent procedure published by the CRREL laboratory (Tice et al, 1982) is given below:

> Distilled, deionized water was added to 60 g of oven-dried Morin clay to form a mixture of 20% water to clay by weight. After mixing, the soil and water were sealed for 1 week to allow for complete moisture equilibration. Then, two replicates were compacted to a wet density of 1.72 g/cm^3 in glass test tubes to a volume of 9 $\pm$0.05 cm^3. A copper-constantan thermocouple was inserted into the center of the soil of one sample to monitor temperature (number 36 gauge wire was used because it does not affect the NMR signal due to displacement of soil). Both test tubes were sealed with rubber stoppers to prevent moisture changes. A grid sample was taken for a water content determination.
>
> Following sample preparation, the test tubes with soil were placed in a precision temperature bath containing an ethylene glycol-water mixture and allowed to equilibrate at the first test temperatue, -16.5°C, overnight. The following morning a background reading on the NMR spectrometer was recorded and the test tubes were sequentially removed from the bath, wiped dry, and measured in the NMR analyzer. The sample temperature and NMR signal amplitude were recorded (elapsed time, about 4 s) and the samples were reinserted in the bath.
>
> After both samples had been analyzed, the bath temperature was then increased by about 2°C. About 30 min was allowed for the samples to attain thermal equilibrium at the new temperature and the measurements were repeated. After being raised to approximately -3°C, the bath temperature was increased at 0.4°C intervals until the samples were completely melted. Above 0°C, NMR readings were obtained at about 2.5°C increments until a temperature of about 18°C was reached. These above-freezing measurements were made to determine how much the NMR signal intensity is affected by temperature and to establish a paramagnetic regression line. Substances that are even slightly paramagnetic, including water, yield decreasing signal amplitudes with increasing temperatures.
>
> Following the last NMR warming determination at about 18°C, a complete cooling curve was obtained by reversing the above procedure. Unfrozen water contents were calculated in the following manner. First the paramagnetic linear regression line was calculated by fitting the thawed experimental data. All NMR signal intensities that increased with decreasing temperatures were

included in the regression. If a reading was lower than 1% of the projected regression line, it was assumed to be partially frozen. After nucleation, a reduction in signal intensity which corresponds to the amount of water present as ice was recorded.

The raw NMR data from the warming run are shown in Figure 3.2.2 for both samples. It can be seen from this figure that the first pulse amplitude increases as temperature decreases for the samples containing no ice, but the first pulse amplitude is reduced when water begins to freeze just below 0°C. Unfrozen water contents are calculated by extending the line drawn through the data points taken with no ice present down to low temperatures by linear regression (solid line, Fig.3.2.5). The unfrozen water content is then calculated as the total water content (determined gravimetrically) multiplied by the distance from the background amplitude reading to the first pulse amplitude reading (A in the figure) and divided by the distance from the regression line to the background amplitude reading (B in the figure).

g) Time Domain Reflectometry

In the last decade, Time Domain Reflectometry (TDR) has been developed as a method of measuring the dielectric properties of soil. The apparent dielectric constant, K_a, is a measure of the capacitance of a soil, or its ability to attenuate electrical energy. Topp et al (1980), in an experimental analysis of the effects of various parameters on K_a, discovered that K_a is almost totally dependent on the soil water content, and is not significantly affected by mineralogy, density, texture, chemical composition and temperature of the soil and pore water. The method was noted for its simplicity of measurement and reproducibility of results. It was also found that ice and dry soil have very similar dielectric properties, both much lower than that of unfrozen water. These factors suggest that the method is applicable to the measurement of the unfrozen water content of frozen soils.

A schematic representation of the TDR system is shown in Fig.3.2.6(a). A fast time step voltage is generated and propagated through the system and a soil sample. A trace of the variation in the amplitude of K_a with time is recorded. An idealized trace is shown in Fig.3.2.6(b). The velocity of the signal as it passes through the soil sample may be deduced from the time of travel through the sample (C-D on Fig.3.2.6(b)) and the length of the sample. The value of K_a is the square of the ratio of this velocity to the velocity of an electromagnetic wave in free space (3.0×10^3 m/s).

Topp et al (1980) produced an empirical relationship between K_a and the unfrozen water content (see Fig.3.2.7). A majority of the measured data on mineral soils fell within $\pm$ 2.5% of this function. Patterson and Smith (1981) reported similar agreement for frozen soils. The major source of error in the measurements is the uncertainty involved in the time measurement from the TDR trace.

Topp et al (1980) measured dielectric properties by TDR using a coaxial transmission line soil column, which consists of an inner rod and outer cylinder (see Fig.3.2.8). This type of transmission line proved to be ideal for sensitivity analyses of water content variation with various controlled parameters, but is inappropriate for the measurement of dielectric properties in situ or on frozen core samples. Parallel transmission lines (see Fig.3.2.9) are better suited for this purpose, since the parallel rods will lessen mechanical disturbance. These parallel rods are commonly spaced at 2.5 - 5.0 cm apart, and are 10 to 35 cm in length. Topp et al (1980) also recommended that procedures for the use of parallel transmission lines be developed so that wetting and drying processes in the soil are not affected by their installation.

Research on the use of parallel transmission lines has been conducted at Carleton University, Ottawa (Smith and Patterson,1981; Patterson, 1980). Measurements of unfrozen water contents of several sands at various temperatures showed strong agreement with the results of other methods.

Smith and Patterson (1981) used the following procedures to study the freezing characteristics of soils.

Experimental Procedures

Freezing Characteristic Curves

When parallel transmission lines are used, a slurried sample is placed in a PVC tube 20 cm long and 5 cm I.D., and allowed to consolidate over a few days. A balanced parallel line probe of 0.3 cm (1/8 in) stainless steel rod is then inserted in the sample; a line length of 17.5 cm was used, with a line spacing of 2.5 cm. The PVC tube is covered with a latex rubber membrane and immersed in a circulating ethylene glycol bath, which permits temperature control to ± 0.01°C for extended periods of time. Freezing is initiated by subjecting the sample to a temperature of about -4°C for 30 to 45 minutes after it has stabilised near 0°C for 24 hours. The sample is then ramped through a temperature cycle and K_a (hence θ_{uf}) determined at each temperature. This type of freezing cell can be used for both freezing and thawing cycles, since tube rupture due to freezing is not a problem.

To compile a freezing characteristic curve takes about 2-3 days for a silt loam, allowing 4 or 5 hours for each point to reach equilibrium. One can check for equilibrium by monitoring K_a a number of times at each temperature until a steady TDR trace is obtained. For a heavy clay at temperatures between 0°C and -1°C, it can take up to 24 hours to reach equilibrium in the sample. A complete curve down to -5°C can be obtained in 4-6 days, depending on the number of points desired.

Freezing Column Experiments

One procedure used to obtain data on the rates and amount of water movement toward the freezing front during closed system

soil freezing is to replicate soil profiles, freeze them for various time periods and then section the profiles to obtain water content with depth gravimetrically. This replication process is time-consuming and can introduce experimental errors which can make the interpretation of results difficult. Also, this approach cannot be used on undisturbed soil cores obtained from the field. Since the TDR technique is a non-destructive method, the need for duplicating soil profiles is removed and the possibility of instrumenting undisturbed soil cores exists (if the core diameter is large enough, say about 12.5 - 15 cm).

A freezing column was constructed to permit controlled sample freezing and water content measurement via the TDR technique. Two cooling plates were used to control the end temperatures, with the top plate at sub-freezing temperatures. Balanced parallel transmission lines, installed horizontally at 2.5 cm intervals along the column length, were used for water content measurement. Closed-system freezing experiments have been carried out initially, to examine the use of the TDR technique for monitoring the desiccation of the unfrozen zone as water migrates towards the freezing front.

Soil samples (of Ellwood clay loam and Cavan loam) were slurried, placed in the column and allowed to consolidate for several days. The column was then insulated, placed in a controlled temperatue chamber (at ~1°C) and the temperature of both cooling plates set to 1°C. Once the sample temperature had stabilized at 1°C, the temperature of the top plate was stepped down to about -4°C to initiate sample freezing. The temperature of the top plate was then set to a temperature of -1°C. K_a (and hence θ_v) was measured throughout the unfrozen soil at the beginning and end of each experiment (which lasted about 120 hours). Also, at the end of the experiment the whole column was cored, using a brass ring corer (2.5 cm in length, 5.1 cm I.D.), to determine the water content profile gravimetrically. Some problems were encountered with this where the soil tended to crumble.

K_a Determination for Low Density Samples

Experiments were performed to obtain K_a vs T°C data for samples with dry bulk densities less than 1 g cm^{-3}. for example, as in the case of soils containing excess ice. A small coaxial freezing cell was designed for these experiments; it is 15 cm long, has an inside diameter of 2.5 cm and a 0.64 cm (1/4 inch) diameter centre conductor. With coaxial freezing cells, care must be taken that the centre conductor is not heaved,

thereby possibly breaking the connection at the BNC connector. To avoid this, a soil slurry is cooled to about 0°C and added in small amounts to the cell. After each addition of soil, the cell is placed in a freezer at -18°C to rapidly freeze the sample. This is repeated until the coaxial cell is filled. The cell is then covered with a latex membrane and placed in the temperature bath.

A sample containing excess ice, but without banded ice, can be obtained if a fine-grained super-saturated slurry is used and is added in small amounts to the cell, since freezing will occur before the particles settle out of suspension. Total water content and bulk density were known since all masses and volumes were determined prior to and following each experiment. By comparing K_a values for low bulk density samples to K_a values for samples of "normal" bulk density, some inference about ice content can be made.

In a number of other experiments, discrete ice lenses were formed by adding water to the cell between soil layers. The ice lenses form impedance contrasts along the transmission line, and produce a signature on the TDR trace.

A combined TDR parallel transmission line-dilatometer test provided simultaneous measurements of unfrozen water contents which agreed favourably. The value of the dielectric constant is very dependent on the frequency of signal generation, especially in the range of 10^2 to 10^5 Hz (Patterson,1980), but not strongly dependent at higher frequencies (10^6 - 10^9 Hz). It is recommended by Patterson (1980) that measurements be made in the latter frequency range.

The TDR method shows promise both for the instantaneous measurement of the unfrozen water content of frozen soils in situ or of frozen core samples, and for the determination of unfrozen water content versus temperature relationships in a relatively short time. The method also offers a great flexibility in system design (Patterson,1980). The independence of K_a from various soil properties indicates that TDR

calibration with individual soils is not necessary, as is the case with other methods.

Williams (personal communication) recommends the concurrent use of Time Domain Reflectometry and Nuclear Magnetic Resonance as complementary measurements of unfrozen water content.

3.2.3 Bulk Density

The bulk density of frozen soils has been shown to be very dependent on temperature, mainly because of the variation in unfrozen water and ice volumes. Since the bulk density of frozen soils is dependent on ice content and structure, it is beneficial to avoid sample disturbance in the density measurements. Conventional laboratory methods, including core and clod methods (McKeague,1978) and the back-calculation of bulk density from dry density and moisture content measurements, involve the destruction of the sample.

Haynes et al (1975) used a method similar to the standard specific gravity test (ASTM C97). A frozen soil sample is first weighed in air and then weighed again while immersed in a fluid of known density. The bulk density of the sample, , may then be calculated from:

$$\gamma = \left(\frac{a}{a-b}\right)\gamma_f$$

where a = weight of sample in air

b = weight of sample immersed in fluid

γ_f = density of fluid

The above tests should be performed in a climate-controlled room. There are several criteria for the choice of fluid for this procedure:

1) The fluid must have a very low freezing point, thus making it adaptable to the low temperatures required for undisturbed frozen soil samples,

2) The bulk density of the fluid, and its variations with temperature must be known. A fluid which does not significantly change in density over the required temperature range is preferable. This requirement makes the test applicable to measuring density variations with temperature.

3) The fluid should be fairly viscous, so that it will not penetrate the sample. The fluid must not dissolve the ice or soil components. Usually the fluid is saturated with water by contact with ice and then the density of the fluid is determined (Heginbottom, private communication).

Haynes et al (1975) used iso-octane. At a temperature of -7°C, iso-octane has a freezing point well below the temperature range of the sample, and does not penetrate into the sample. The procedure was not considered to have produced any detrimental effects on the sample for triaxial compression testing.

The Manitoba Soil Survey used methods similar to that of Haynes et al (1975). Bulk densities of frozen organic soil cores are measured by immersion in mercury (McKeague,1978).

3.2.4 Salinity

The salinity of a frozen soil is of particular importance to its engineering behaviour, most notably in its effects on the unfrozen

water content. A procedure for measuring soil salinity by electrical conductivity is included in section 3.10.2.

3.2.5 Unfrozen Soil Classification and Index Tests

A number of classification and index tests for unfrozen soils are also applicable to frozen soils. Many of these tests are standardized by the American Society for Testing and Materials (1982). ASTM continually revises and updates its testing procedures, and publishes these revisions annually. The ASTM standard index and classification tests for unfrozen soils are listed below.

D421-58(1978)	Dry preparation of soil samples for particle-size analysis and determination of soil constants.
D422-63(1972)	Particle-size analysis of soils.
D423-66(1972)	Test for liquid limit of soils
D424-59(1971)	Test for plastic limit and plasticity index of soils.
D425-79	Test for centrifuge moisture equivalent of soils.
D427-61(1974)	Test for shrinkage factors of soils.
D653-81	Standard definitions of terms and symbols relating to soil and rock mechanics.
D698-78	Test for moisture-density relations of soils and soil-aggregate mixtures using 5.5 lb (2.49kg) rammer and 12 in (305 mm) drop.

D854-58(1979)	Test for specific gravity of soils
D1140-54(1971)	Test for amount of material in soils finer than No.200 (75 m) sieve.
D1557-78	Test for moisture-density relations of soils and soil aggregates mixtures using 10lb (4.54kg) rammer and 18 in (457 mm) drop.
D1558-71(1977)	Test for moisture-penetration resistance relations of fine-grained soils.
D2049-69	Test for relative density of cohesionless soils
D2216-80	Laboratory determination of water (moisture) content of soil, rock, and soil-aggregate mixtures.
D2217-66(1978)	Wet preparation of soil samples for particle-size analysis and determination of soil constants
D2419-74(1979)	Test for sand equivalent value of soils and fine aggregate
D2487-69(1975)	Classification of soils for engineering purposes
D2488-69(1975)	Recommended practice for description of soils (visual-manual procedure)
D2607-69	Classification of Peats, Mosses, Humus, and related products.

Detailed procedures for some of the above tests are included in Bowles (1970). A number of alternate procedures for soil testing are given by McKeague (1978).

TABLE 3.2.1 Description and Classification of Frozen Soils (after Linell and Kaplar, 1963)

I: Description of soil phase (independent of frozen state)	Classify soil phase by the unified soil classification system								
	Major group		Subgroup				Classify soil phase by the unified soil classification system		
	Description	Designation	Description		Designation		Field identification	Pertinent properties of frozen materials which can be measured by physical tests to supplement field identification	Thaw characteristics
II: Description of frozen soil	Segregated ice not visible by eye	N	Poorly bonded or friable		Nf		Identify by visual examination; to determine presence of excess ice, use procedure under note (3) and hand magnifying lens as necessary; for soils not fully saturated estimate degree of ice saturation (medium, low); note presence of crystals or of ice coatings around larger particles	In-place temperature Density and void ratio *a.* In frozen state *b.* After thawing in place Water content (total H_2O, including ice) *a.* Average *b.* Distribution Strength *a.* Compressive *b.* Tensile *c.* Shear *d.* Adfreeze Elastic properties Plastic properties Thermal properties Ice crystal structure (using optical instruments) *a.* Orientation of axes *b.* Crystal size *c.* Crystal shape *d.* Pattern of arrangement	Usually thaw-stable
			Well bonded	No excess ice	Nb	n			
				Excess ice		e			
	Segregated ice visible by eye (ice 25 mm or less thick)	V	Individual ice crystals or inclusions		Vx		For ice phase, record the following as applicable Location, Orientation, Thickness, Length, Spacing, Hardness, Structure, Color (per part III below); Size, Shape, Pattern of arrangement Estimate volume of visible segregated ice present as percent of total sample volume		Usually thaw-unstable
			Ice coatings on particles		Vc				
			Random or irregularly oriented ice formations		Vr				
			Stratified or distinctly oriented ice formations		Vs				
III: Description of substantial ice strata	Ice greater than 25 mm thick	ICE	Ice with soil inclusions		ICE + soil type		Designate material as ice and use descriptive terms as follows, usually one item from each group, as applicable: Hardness: hard, soft (of mass, not of individual crystals) Structure: clear, cloudy, porous, candled, granular, stratified Color: colorless, gray, blue Admixtures: contains few thin silt inclusions	Same as part II above, as applicable, with special emphasis on ice crystal structure	
			Ice without soil inclusions		ICE				

TABLE 3.2.2 A Geotechnical Classification of Permafrost
(after Ziwang, 1979)

Soil Nomenclature	Total Moisture Content of Frozen Ground (%)	Thaw Settlement Classification	Type
Gravelly and pebbly soil very coarse sand, coarse sand, medium sand (amount of fines<15%)	W<10	no thaw settlement	I
	W>10	minor thaw settlement	II
Gravelly and pebbly soil, very coarse sand, coarse sand, medium sand (amount of fines > 15%)	W<12	no thaw settlement	I
	12<W<18	minor thaw settlement	II
	18<W<25	moderate thaw settlement	III
	W>25	major thaw settlement	IV
Very fine sand, fine sand	W<14	no thaw settlement	I
	14<W<21	minor thaw settlement	II
	21<W<28	moderate thaw settlement	III
	W>28	major thaw settlement	IV
Clayey soil	W<Wp*	no thaw settlement	I
	Wp<W<Wp + 7	minor thaw settlement	II
	Wp + 7<W<Wp + 15	moderate thaw settlement	III
	Wp + 15<W<Wp + 35	major thaw settlement	IV
Soil containing ice layer	W>Wp + 35	major thaw subsidence	V

* For granular soil, the critical water content for initiating thaw settlement is used in place of Wp. Peaty soils and soils containing decomposed vegetable matter are not included in this table.

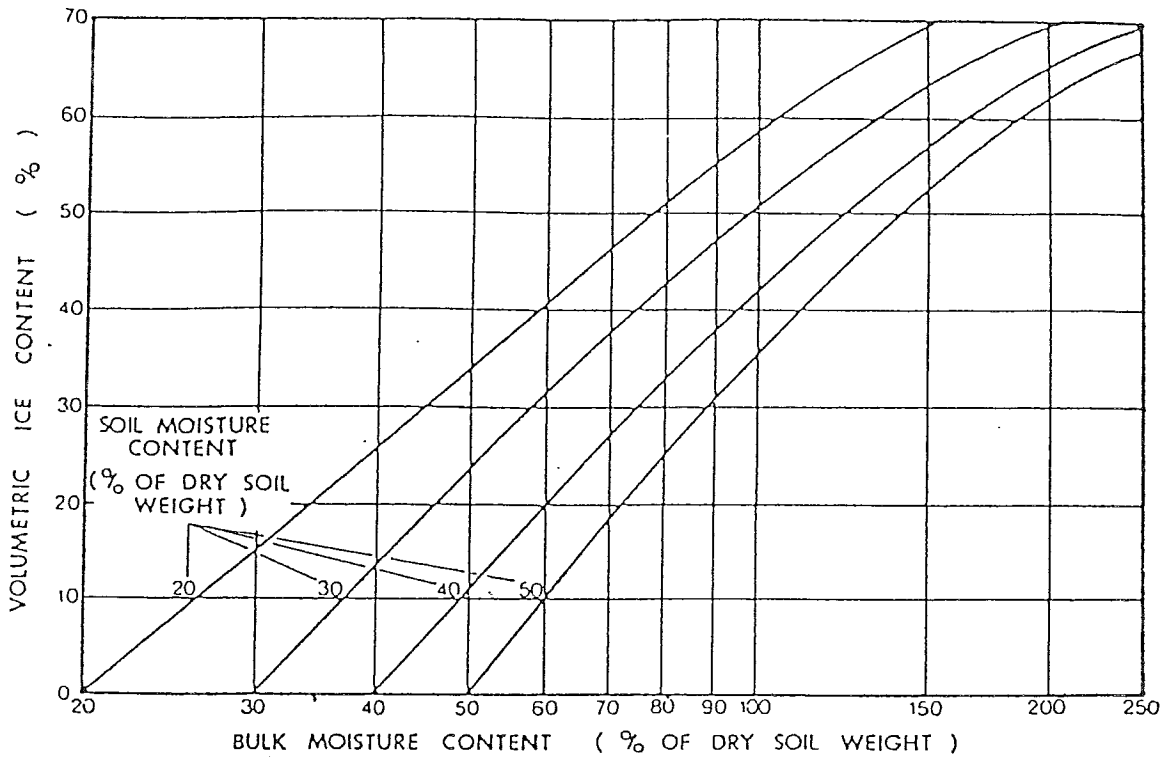


FIGURE 3.2.1 Graphical Solution of Bulk Moisture and Volumetric Ice Contents (after Savigny, 1977)

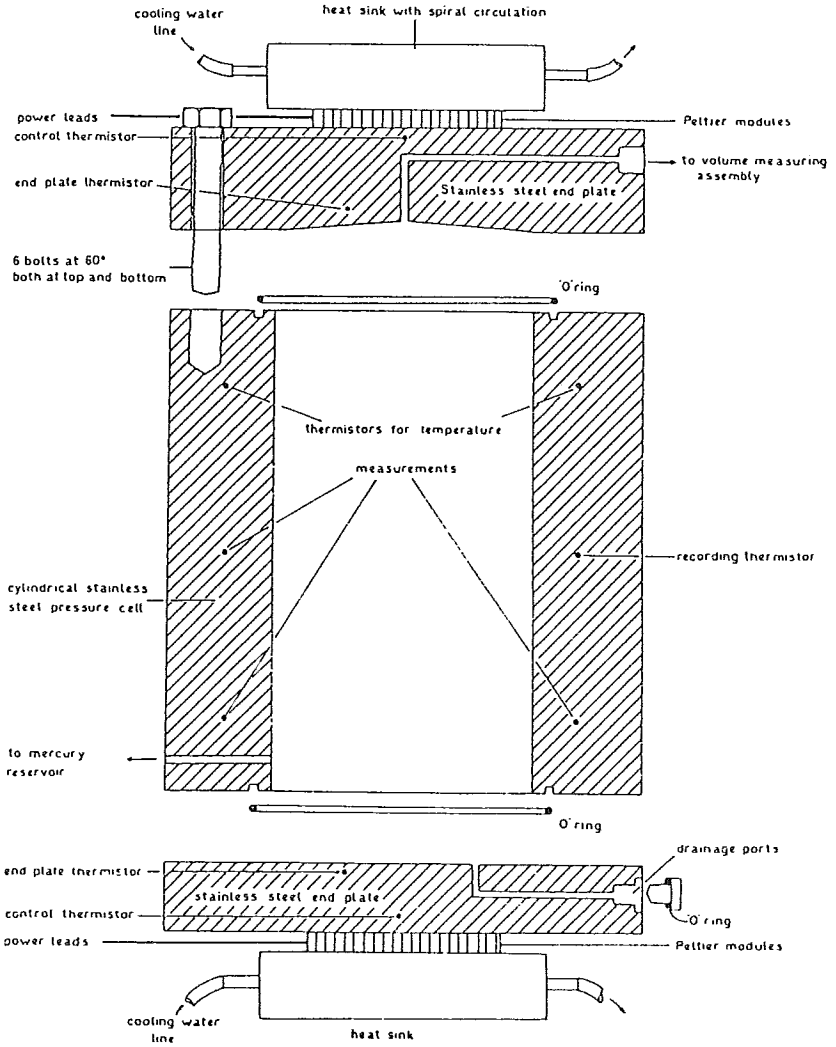


FIGURE 3.2.2 Dilatometer and Auxilliary Equipment
(after Williams, 1976)

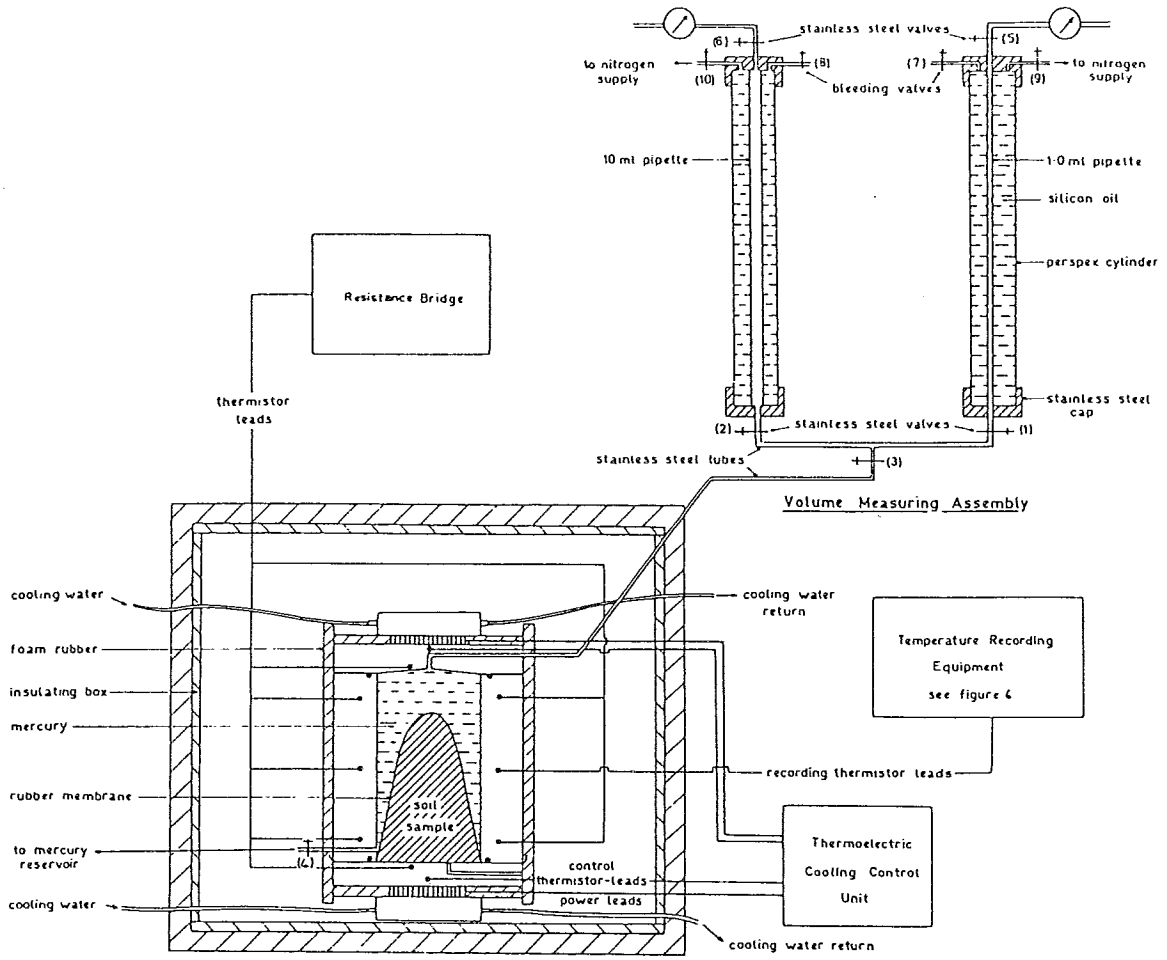


FIGURE 3.2.3 Dilatometer Cell (after Williams, 1976)

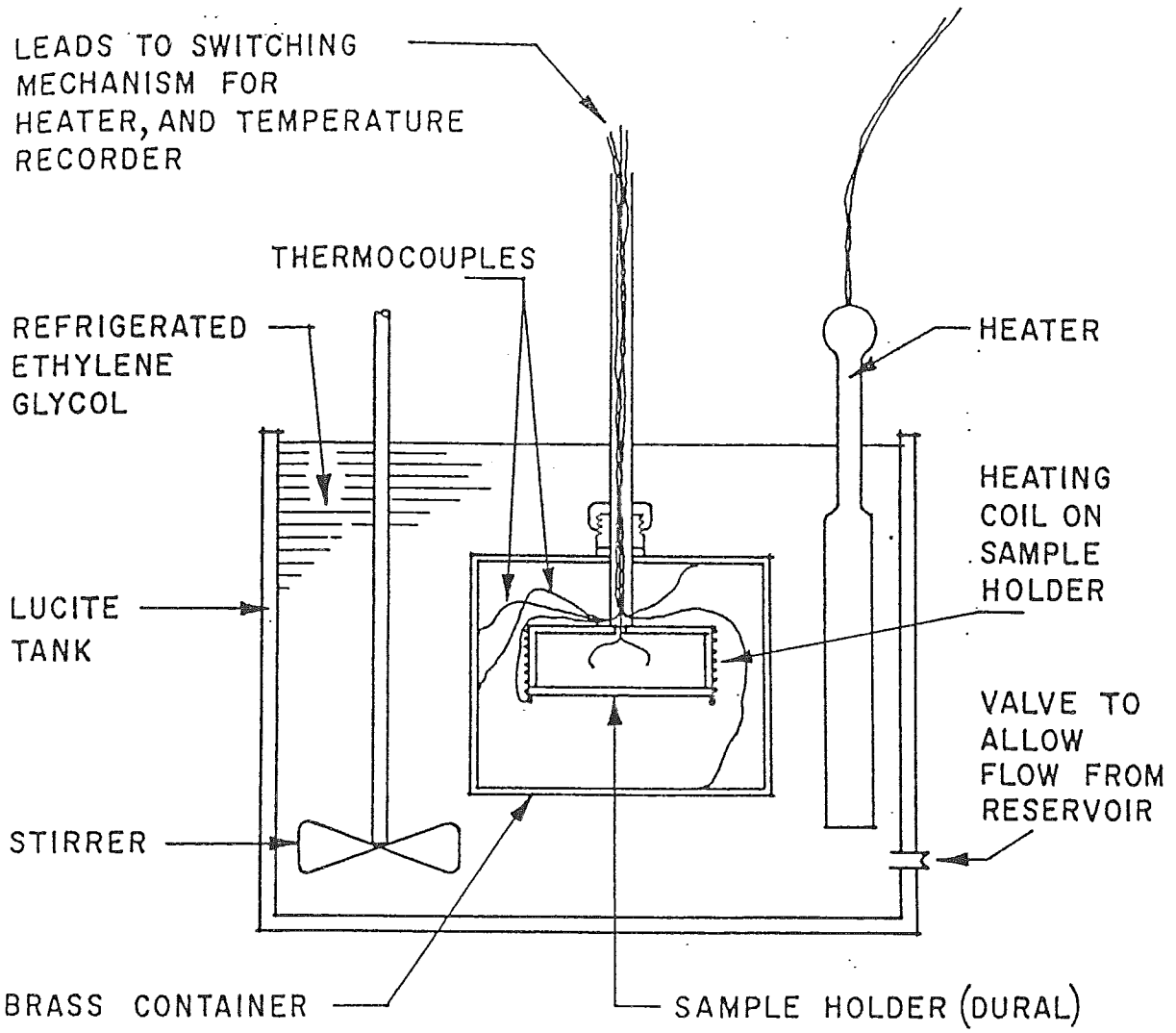


FIGURE 3.2.4 The Calorimeter (after Williams, 1963)

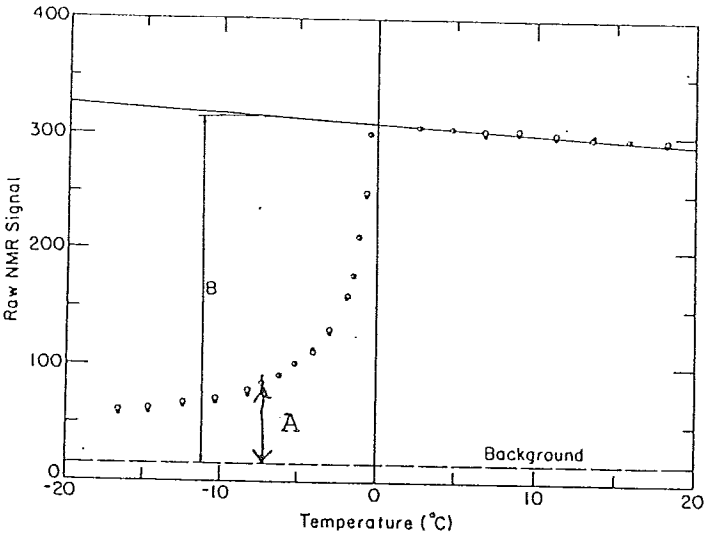


FIGURE 3.2.5 Typical Plot of NMR Signal Versus Temperature (after Tice, et al, 1982)

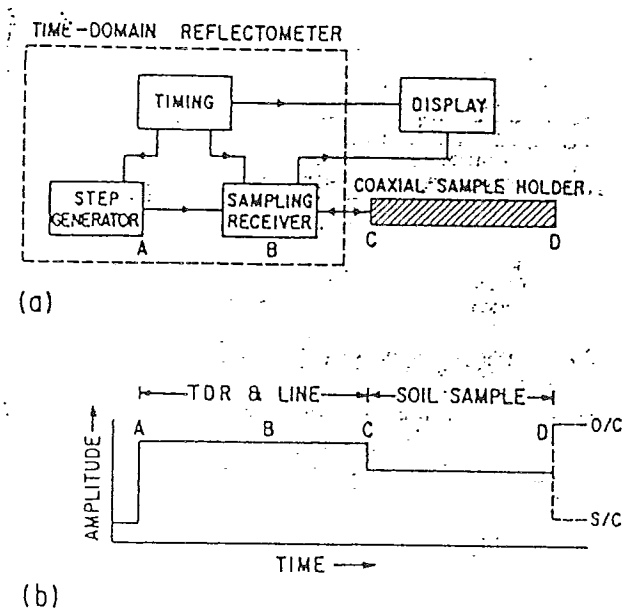


FIGURE 3.2.6 (a) Block Diagram of Time-Domain Reflectormeter
(b) Idealized TDR Output
(after Topp, et al, 1980)

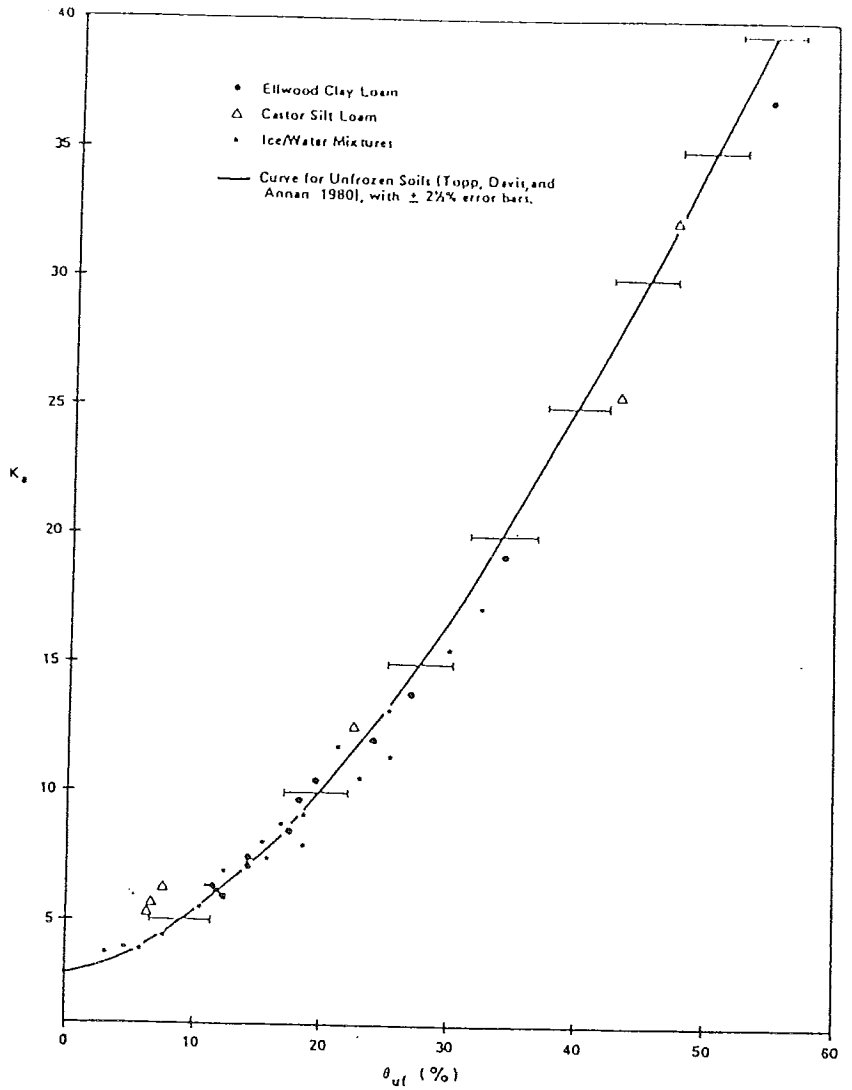


FIGURE 3.2.7 Variation of dielectric constant K_a, with Unfrozen Water Content (after Patterson and Smith, 1981).

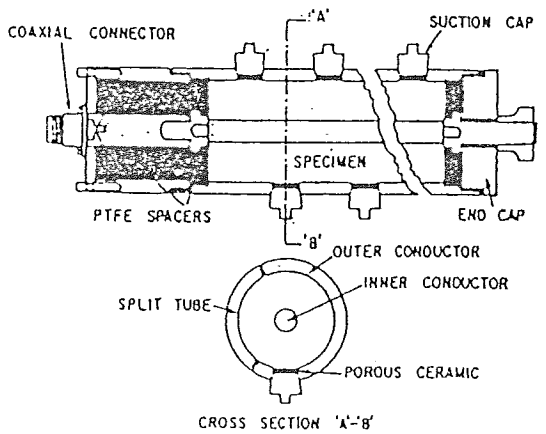


FIGURE 3.2.8 Coaxial Transmission Line Soil Column for measurement of dielectric properties (after Topp, et al, 1980).

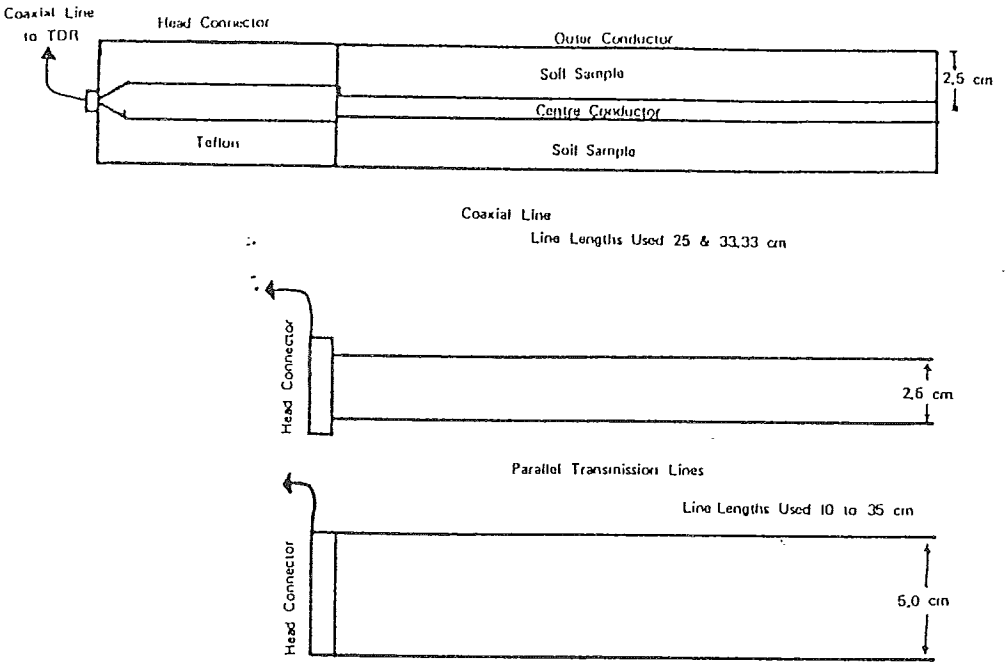


FIGURE 3.2.9 Transmission Lines for TDR measurements (after Patterson, 1980).

3.4.2.4 Testing at Michigan State University

A. After J. Alnouri (1969)

(i) Apparatus

The same triaxial cell and cold bath were used for the differential creep tests and the constant axial strain-rate tests. The sample rested on a brass pedestal in a standard triaxial cell. The pedestal was mounted directly on a force transducer (DYNI SCO Model TCFTS-1M), which has a rated capacity of 1000 pounds with overload to 1500 pounds. Fig.3.4.4 shows a schematic diagram of the sample placement in the triaxial cell. The triaxial cell was entirely submerged in a coolant, an equal part mixture of ethylene glycol and water. The coolant was maintained at a constant test temperature by circulating through a microregulator controlled cold box.

Before any testing was carried on, the temperature control was calibrated by measuring the temperature at the vicinity of the sample inside the triaxial cell, and the temperature at a fixed location in the low-temperature bath. The temperature of the sample was measured by placing a copper-constantan thermocouple adjacent to the sample at mid-height, and another one in a bath of distilled, deionized, melting ice used as a reference point. The temperature was obtained by measuring the E.M.P. with a potentiometer (Leeds and Northrop Model K-2) and using an E.M.P.-Temperature calibration chart. At the same time the temperature was measured at specific locations in the low-temperature bath by a thermometer with scale divisions of $0.1^{o}C$. These temperature measurements were carried on over a period of twenty-four hours. It was observed that the temperature varied by no more than $0.05^{o}C$. The bath temperature control was set at the desired test temperature and left for three days until the temperature at the bath reached a constant value of the desired test temperature. Prior to testing the sample was left for twenty-four hours in the low-temperature bath to insure temperature equilibrium in the sample.

The axial pressure was supplied through the loading ram at the top of the triaxial cell. The confining pressure was supplied through a valve at the base of the triaxial cell from a constant pressure unit. The pressure unit was self-compensating mercury control apparatus, which was capable of supplying a constant pressure to a triaxial cell for testing over long periods. The pressure was provided through the valve assembly by the difference in head between the surface of mercury in the upper moving

assembled correctly and that no hose connections were leaking. Monitoring was carried out throughout the stabilization period to check instrument performance.

By the end of the stabilization period zero readings for the LVDT, pressure transducer, and thermistor were well established. The load requirement for the desired axial stress was placed on the lever arm which was supported by a hydraulic jack. The jack was lowered and monitoring commenced at time zero. Loading took place over a period of between 3 and 5 seconds.

Readings during the first hour were recorded by hand through remote monitoring of the data acquisition system. All subsequent readings were recorded on the Techtran recorder. At least one reading was obtained within the first 45 seconds and approximately 15 within the first hour. From the second to at least the sixth hour the reading interval was set at 10 minutes and thereafter 1 hour.

Data were transferred at regular intervals to the IBM 360 computer. The results were processed intermittently by computer so the test progress could be accurately monitored.

As vertical deformation accumulated, the lever was maintained in a horizontal position by adjusting the reaction device on the lever assembly. For tests which extended for more than approximately 2 days, adjustments to the load were made at intervals of 0.5% strain to maintain constant stress conditions.

For tests where secondary creep behaviour was well established over a 50 to 70 day period with no indication of acceleration into tertiary mode, the samples were stage loaded to at least one higher axial stress level following the same procedure outlined earlier in this section.

Cells were dismantled within a few hours of sample failure or termination of the test. All instrumentation and pressure and temperature regulation lines were disconnected, and a dummy heat-exchange coil was installed inside the insulated cabinet to minimize thermal disturbance to other in-line tests.

axial strains by assuming that the sample volume did not change. Deformations occurring over time intervals of several days were normally quite small, so a constant axial stress (±0.5%) could be maintained quite easily.

(ii) After Savigny (1980)

Samples were prepared in a soil preparation laboratory where the ambient temperature was maintained between -3°C and -7°C. The ends were trimmed with a band saw before the sample was mounted in a soil lathe and turned to an outside diameter of approximately 10 cm. Finally, the ends were trimmed parallel on an overhead milling machine.

The dimensions and weight of the sample were noted and photographs taken to record the ice structure. Engineering properties were routinely determined from the several centimeters of core trimmed at each end. Since the presence of varying amounts of ice precluded any possibility of obtaining representative water contents, bulk density was reported for the purpose of comparing the relative ice content of different samples.

When trimming was completed, holes for centering pins were drilled into the top and bottom of the sample and it was put in place on the lower platen. The upper platen was set in place and the loading ball set in the recess at the top of the platen. The upper part of the cell was lowered over the sample, and when in place, the position of the loading ball was inspected through the load-ram annulus at the top of the cell.

Light paraffin oil was introduced to the cell through the load-ram annulus until the upper load platen was covered. The cell was then placed in the insulated box, and while topping of the paraffin oil continued, the load ram, instrumentation, confining pressure lines, and temperature control lines were assembled. When paraffin oil began to displace through the pressure relief valve at the top of the cell, all valves were closed, the supply line was disconnected, and the insulated cabinet was closed. The lever and load transfer system were put in place, and a nominal axial load, marginally greater than the reaction of the load ram to the planned confining pressure, was applied. Finally, circulation of the temperature control fluid was begun and the confining pressure was applied.

The system was allowed between 24 and 36 hours to come to temperature and stress equilibrium. Within the first few hours a check was made inside the cabinet to ensure that all equipment had been

testing, but adopting oil as a confining fluid eliminated the necessity to jacket the specimens so their use was discontinued.

Once the load platens had been lubricated, creep specimens were located on the pins and set up with the load cap in place. The upper half of the creep cell was then lowered and clamped onto the base to make a seal. Circulation of refrigerated fluid through the heat exchangers was commenced while the cell was being filled with paraffin oil. It should be noted that prior to each test, the thermistor probe calibration was checked against an ice bath at $0^{o}C$. The temperature sensor was then lowered into position through a Swagelok bulkhead adaptor and, as a last step, the exterior of the cell was enclosed in Styrofoam insulation.

A small axial stress was applied to seat the load platens against the test specimen. Valves were then closed off inside the cold room so the cell pressure and axial stress could be adjusted externally without applying any load to the sample. The air pressure regulators used to control these stresses were located on a control panel outside the cold room. This arrangement avoided problems which were encountered with the condensate freezing and interfering with normal operation when the regulators had been located in a sub-freezing environment. Once the air pressures had been set at appropriate values, cell pressure and axial load were controlled by opening valves on lines located inside the cold room. Cell pressures were applied a minimum of three days prior to increasing the deviatoric stress and initiating of creep. Theis provided some time for adjusting the test temperatures and allowing the sample to reach thermal equilibrium.

The creep tests were usually run with two cells set up side by side in the same load frame and enclosed within a single insulated cabinet. Once the load platens had been seated, LVDT's were clamped to the load rams on each cell. Following adjustments to the LVDT output voltage, the insulated cabinet was closed and sealed. When conditions were considered stable, initial readings were taken and the valve controlling the Bellofram was opened which resulted in the sudden application of axial load. Air pressure in the Bellofram built up to the desired level within a matter of a few seconds. During each creep, cell pressures and axial loads were checked for constancy at intervals of one to two days. The axial load was adjusted periodically to account for changes in the cross-sectional area that was calculated from

transfer system was aligned during fabrication to ensure no eccentric loads affected the load ram.

Confining pressure was supplied by an air over paraffin oil, pressure-regulated supply reservoir. The regulator and air supply were situated outside of the controlled temperature laboratory to eliminate the possibility of water vapour condensing and freezing in the lines. The pressurized oil line was connected to a manifold inside the laboratory, from which each cell was supplied and could be independently controlled. The cells were filled by connection to a larger, pressure-regulated supply reservoir.

The instrumentation for each apparatus included a thermistor and a linearly variable differential transducer (LVDT); an electrical resistance strain-gauge diaphragm pressure transducer was mounted in the central pressure line outside of the laboratory. The thermistor was an Atkins PR99-3 calibrated against a quartz resistance thermometer[1], and mounted in stainless steel tubing as described earlier in this section. The LVDT was a Hewlett-Packard 24 DODT capable of measuring displacements as small as 1.0×10^{-4} cm. It was mounted so as to measure the displacement of the load ram relative to the top of the cell. The pressure transducer was capable of measuring pressure changes as small as 0.15 kPa. Both the LVDT and the pressure transducer were calibrated with equipment of local design.

Data were recorded on a Techtran cassette recorder attached to a data acquisition system.

B. Triaxial Creep Tests - Procedures

(i) After Roggensack, W.D. (1977)

Setting up the isothermal confined creep tests was performed entirely within the confines of the cold room. Once the equipment had been cooled to subfreezing temperatures, the load platen surfaces were prepared with surface lubricants. Fig.3.4.3 shows a sectional view of the base pedestal with details of the friction reducing precautions. The contact surfaces of the pedestal and load cap had been covered with a thin sheet of Teflon. This was coated with an even film of Dow-Corning high vacuum grease. A second film of lubricant containing molybdenum disulphide was then applied. Finally, a thin sheet of neoprene rubber was placed on top of each lubricated surface to separate the sample from the grease. Neoprene membranes were used in preliminary

[1] See Sego (1980,Appendix B) for specifications of this thermistor and details of the calibration procedure.

3.4.2.3 Testing at the University of Alberta

A. After Roggensack (1977) and Savigny (1980)

(i) Apparatus

The equipment used by Savigny (1980) is basically the same as that used by Roggensack (1977) and only Savigny's will be described in detail. The main difference in the apparatus is that Roggensack (1977) applied axial load using a Bellofram air cylinder with a rolling diaphragm whereas Savigny (1980) used a lever apparatus. Savigny's apparatus is described below:

> Creep tests at the U. of A. were carried out in specially designed triaxial cells fabricated in the U. of A. Civil Engineering machine shop. The cell details are illustrated schematically in Fig.3-4-1. Samples were tested without membranes in a confining medium of light paraffin oil. Temperature of the oil was monitored by a thermistor bead embedded at the head of a stainless steel tube inserted through the cell cover to approximately mid-height beside the sample. The sample temperature was assumed to be identical to that of the oil. Temperature control was provided by a solution of ethylene glycol regulated in a temperature control bath and circulated through heat-exchange coils wrapped in a circumferential pattern around the sample.
>
> Details of the overall apparatus are shown schematically in Fig.3-4-2. The cell was placed on a bakelite centering plate inside an insulated cabinet. The cabinet was mounted on a frame of channel iron and the entire apparatus was situated in a controlled temperature laboratory maintained at between $-3^{o}C$ and $-7^{o}C$. A Hot Pack Model 603340 temperature control bath was elevated over a row of four apparatuses. The unit was equipped with a manifold and the four cells connected in parallel with taigon tubing. A special pump was used in order to adequately service each cell.
>
> A level assisted, dead-load loading frame was used to apply constant load. This was transferred to the upper platen via a frame narrowly fitted outside of the insulated box. The entire load

load is maintained for a shorter period, while for clayey, particularly high-temperature frozen soils, the load is maintained for a longer period.

In all cases the stages must be maintained for at least 24 hrs.

5) Stage loading tests are conducted in a similar manner to creep tests. The first stage is applied to a prepared specimen, after which the axial and cross-sectional deformations are measured. The time intervals between readings are fixed in accordance with para.12 above. During the test the magnitude of the acting load is adjusted so that the stress in the specimen remains constant.

6) When the given time has elapsed, the load is rapidly but smoothly increased to σ_2 and the test is then conducted as for the previous stage. As soon as the period of action of the second loading stage has elapsed, additional loading is applied to the specimen, and so on until the test has been completed. The number of loading stages should not be fewer than six or seven. The test is considered complete if, during one stage of the series (but not less than the 6th), progressive flow, characterized by an increase in the deformation rate, is achieved.

7) The second specimen is tested for creep at one constant value of applied stress σ = const.

8) The value of the given stress is calculated so that by the end of the set time period (6 - 8 days) progressive flow will have occurred. The value of stress σ is determined as a fraction of the value of the conditionally instantaneous ultimate strength and is assumed to be equal to 0.4 σ_0.

9) If, during the test, the specimen fails in less than 6 - 8 days or the deformations become stabilized, the test must be repeated, the value of the applied stress σ = const having been appropriately decreased or increased.

18) Each specimen is unloaded after being tested. The load is removed quickly, and immediately afterwards the axial deformation of the sample is measured. Subsequent deformation measurements are carried out in 2, 4, 8, 15, 30 seconds; 1, 2, 4, 8, 15...minutes; respectively, so that the intervals of time between readings are always increased by a factor of two ($\Delta t_{i+1} = 2\Delta t_i$). The test is continued until the deformations are stabilized.

Tests may also be carried out by loading/unloading the specimens in stages. The number of test cycles (loading-unloading) at one temperature must be at least five or six.

19) Using the data obtained for each test, a curve is traced in relative deformation - time coordinates and reflects the process of deformation recovery in time.

(iv) Simplified Method of Determining Creep Characteristics

1) The method recommended here may be used to obtain rough estimates of creep characteristics when it is not possible to prepare the required number of identical specimens or when it is necessary to reduce the overall test period.

2) The creep characteristics are determined from the results of testing two identical specimens, each of which is loaded by a different method.

3) The first specimen is loaded in stages. The magnitude of each stage is determined as a fraction of the value of the conditionally instantaneous ultimate strength σ_0, found by rapid load action tests. The load for the first stage is assumed to be close to 0.1 of the value of σ_0. In the second and subsequent stages the load is progressively increased, the load values being determined by the formula,

$$\sigma_i = \frac{n}{10}\sigma_0 ,$$

where σ_i is the stress being determined; σ_0 is the ultimate strength with rapid load action, n is a factor assumed to be equal to the series number of the loading stage.

4) Each stage of the load is maintained for the same time period, the length of which depends on the soil texture and the test conditions. For sand and low-temperature frozen soils, each

include all the stages of deformation, but will be terminated at the stage of irregular creep (if the rate of deformation being measured continually decreases for each subsequent reading), or in the steady flow stage (if the deformation rate is constant).

The maximum time interval for the tests is determined with respect to the purpose of the tests and the technical resources:

a) If the tests are conducted to determine the characteristics of frozen soils for a long-term load (for example the foundation soils of buildings), the duration of the tests will depend upon technical considerations, but must not be less than 10-15 days.

b) If the tests are conducted to determine the characteristics of frozen soils subjected to a load for a limited, short period of time - several hours or days - (for example, for static evaluations of protective enclosures of frozen soil formed when cutting various holes and trenches with the aid of artificial freezing), the maximum duration of the tests should correspond to the period during which it is required to keep the soil in a frozen state*.

15) On completion of each test, a creep curve is constructed. For this we take the absolute deformation (λ_i) values and the time (t_i) values corresponding to them, we determine the relative deformation $\epsilon=\lambda_i/h$ (where h is the initial height of the specimen) and construct a graph in coordinates of $\epsilon = t$.

As a result of testing all the specimens in a given series, we obtain a series of creep curves (for a given soil temperature) in which each curve corresponds to its constant compressive stress value

$$\sigma_1 \gg \sigma_2 \gg \sigma_3$$

16) Tests have been carried out correctly if the resulting series of creep curves satisfies the following conditions:

a) The creep curves do not intersect or lie upon each other.

b) A straight line drawn parallel to the axis of coordinates for any moment of time, t, intersects at least five creep curves, in which case it will be possible to construct curves in stress-deformation coordinates through these points.

17) Where it is necessary to differentiate between recovering and residual creep deformations and, in addition, to isolate elastic initial deformations, creep tests are carried out by unloading the specimens.

---

* Literally "period of work of the frozen ground". Transl.

minute. As the deformation rate decreases, i.e. when deformation increases are no longer recorded during a one minute interval, the intervals between readings are progressively increased to $\Delta t_i = 2\Delta t_{i-1}$. Accordingly, readings are taken every 2, 4, 8, 15, 30 minutes, 1 hour, 2 hours, etc., but no less frequently than every 8 hours. In selecting the time interval, we must allow for the fact that the deformation increase during t between subsequent readings should not exceed 1.0 mm, otherwise the time between reading will have to be adjusted.

b) If in not less than three successive measurements the deformation rates are practically uniform, it is assumed that the stage of constant velocity flow has been reached. In this stage the deformation measurements are made at uniform intervals of time. The time interval between readings is assumed to be equal to the value of Δt between the final readings during the transition from the irregular creep stage of constant velocity flow.

c) In the progressive flow stage, the onset of which is characterized by an increase in the rate of deformation, the readings are again taken more frequently. The interval between readings is decreased in stages in proportion to the increase in the deformation rate, and is determined by the relationship

$$\Delta t_i = 1/2\, \Delta t_{i-1}.$$

Having regard to the specific test conditions which determine the nature of the deformation of the specimen, it may prove expedient to modify the above relation slightly and take readings either more or less frequently, depending on how the deformation process develops.

13) The tests are considered complete if:

a) The specimen fails (for brittle soils).

b) The deformation of the specimen reaches a value 50% higher than the deformatin at which the stage of progressive flow occurred (for soils subject to viscous deformation).

c) Stabilization of deformation occurs, in which case stabilization is considered to have been reached if the increase of relative deformation, , does not exceed 0.0001 during the following intervals of time: for sand - 6 hours, for sandy loam - 12 hours, for loam and clay - 24 hours.

14) Taking into account the fact that the process of frozen soil creep may be extremely prolonged and under small stresses may extend to several months or even years, the duration of the tests is limited to an interval of time long enough to permit the creep and long-term strength characteristics to be determined. In this case, some of the tests in a given series will not

the increase in the area of the specimen reaches no more than 5%.

8) If the tests are conducted without the stress being automatically controlled, it is necessary to record the lateral deformation and to increase the load P as soon as the area of the specimen varies by the amount indicated above. The corresponding value of load P is obtained from the table. If the tests are conducted with automatic load control, the radial deformation gauge is connected to the automatic control system of the instrument, which alters the load in accordance with the variation pattern of the specimen area.

9) The frozen soil specimen is placed in the press, great care being taken to ensure that it is correctly centered and kept at the given temperature for not less than 20-30 minutes prior to the test.

Smoothly, and guarding against impact, the load, which is gradually increased to the given value, is applied to the sample. The time during which the load reaches the given value must be the same in all the tests and should be approximately 30 seconds.

10) The deformation gauge or the automatic measuring device, is set at zero before the load is applied. However, measurement of creep deformation begins the instant the load reaches the given value. The readings at this instant are taken as zero readings.

11) The deformation rate for each interval of time between measurements is calculated during the test

$$v = \frac{\lambda i - \lambda i-1}{t_i - t_{i-1}} \text{ mm/min}$$

where v is the rate of deformation; $\lambda_i - \lambda_i - 1$ is the deformation increment; $t_i - t_{i-1}$ is the time variation.

12) The time intervals between deformation measurements are selected taking into account the deformation rate of the specimen and the stage of deformation in which the creep process takes place:

a) In the irregular creep stage the time intervals between readings are assumed to be as follows. At the beginning, if the deformation rate is high, readings are taken at least every

3) The specimens are subjected to different stresses, each stress remaining constant for the duration of the given test, and the soil temperature remaining constant for the entire series of tests.

Axial and radial deformations are measured during the test.

4) The load applied to each of the specimens is determined as some fraction of the 'instantaneous' strength (σ_0) determined by rapid action load tests. The first specimen is subjected to a compressive stress σ_1, approximately equal to 0.9 of σ, and the second and succeeding specimens to ever-decreasing stresses $\sigma_1 \gg \sigma_2 \gg \sigma_3 \gg \sigma_4 \ldots$, the values of which are determined from the expression

$$\sigma_i = \sigma_0 \left[\frac{1}{} - \frac{n}{10}\right]$$

where σ_i is the stress applied in the given test, σ_0 is the ultimate strength at rapid load action, n is the factor which for specimens 1 to 9 is assumed to be equal to the series number of the specimen being tested. For the 10th and succeeding specimens (if more than 10 are tested), the value of n may be taken as 9.25, 9.50, 9.75, etc.

5) In uniaxial compression creep tests the cross-sectional area of the specimen increases in proportion to the deformation. Thus, in order to maintain a steady stress, the load must be increasing during the test in proportion to the increase in the area of the specimen. The value of the effective load at any moment of time is determined from the expression $P = \sigma F$ kg, where σ is the stress in the specimen which must be maintained at a constant value, in kg/cm^2; F is the area of the specimen in cm^2.

6) The most efficient way of varying the effective load, P, needed to maintain constant stress, σ= const, is by means of an automatic adjusting device (creep machine). If this device is not available, load P may be varied by the usual load increment method.

7) To facilitate computation of the value of load P it is necessary to compile a subsidiary table containing the indicated growth intervals of the diameter of the specimen d and the corresponding values of the calculated area, F, and the acting load P (at σ=const). The load on the specimen is increased when

tional area also changes (it decreases for uniaxial compression and increases for shear and tension).

A constant stress is achieved by changing the value of the applied load in proportion to the change of the cross-sectional area of the sample (the load is increased or decreased depending upon the type of deformation).

(ii) Tests for Uniaxial Compression and Tension

To test frozen soils for creep and long-term strength in uniaxial compression, presses and testing machines of various designs may be used which allow performance of tests with a wide range of loads. Lever and dead weight presses are also used.

Experiments for uniaxial compression are conducted with samples in the shape of a cylinder, or a rectangular parallel-piped with a cross section. In addition, to reduce the influence of friction along the end planes of the sample, the ratio of the height of the sample to its diameter is chosen larger than, or equal to 2 - 2.5. During preparation of the samples, the end planes are very carefully processed, since for an uneven surface the stresses concentrate and lower the strength of the sample. Lubricating the end planes of the samples is not permissible; such lubrication would change the direction of the tangential stresses and give rise to tensile forces in the sample. To avoid bending during deformation of the sample, the end planes must be maintained absolutely parallel.

For creep and long-term strength tests for frozen soil in tension, presses identical to the previous ones are used. However, special grips are used. The samples are machined into a dog-bone shape with an elongated neck, which guarantees a minimum stress-concentration in the regions adjacent to the grips.

(iii) Uniaxial Creep Test Procedure

Long-term Load Action Tests

1) Long-term load action tests are conducted to determine the calculated characteristics of creep and long-term strength of frozen soils. These tests consist of determining deformations , evolving in time, t, when subjected to constant stress, σ.

2) The tests are conducted with a series of identical specimens of frozen soil. In uniaxial compression tests the number of specimens in a series is 8 - 10.

sian test procedures, though the test philosophy and methods reported are essentially the same.

Detailed procedures for various creep tests are documented below:

3.4.2.2 After Vyalov (1965)

(i) Apparatus

Vyalov (1965) defines the basic criteria that must be satisfied when selecting equipment for creep testing of frozen soil. These criteria are summarized below.

To choose an apparatus for testing frozen soils for creep and long-term strength for various types of deformation, consideration must be given to the fact that the strength of frozen soil varies to a significant degree, depending upon composition (mechanical and chemical), conditions of moisture structure, and even upon conditions under which the experiments are conducted. Therefore, the apparatus must possess sufficient strength and must also guarantee the necessary accuracy, especially in the range of small loads. These requirements may be satisfied by an apparatus with several scales, or by a complex use of several apparatuses with different strengths.

Before testing, samples should be maintained at the planned test temperatures.

The necessary conditions for studying creep and long-term strength of frozen soils are:

1) maintenance of a constant sample temperature throughout duration of the test; this condition must be strictly observed especially for high temperatures (close to $0^{o}C$) which correspond to the range of intensive phase changes;

2) preservation of a constant stress through the test.

Since the cross-sectional area of the sample (when tested for creep) may change significantly during the deformation process, i.e. the cross-sectional area increases for compression and decreases for shear and tension, the stress in this cross-sec-

specifications for sample preparation and testing procedures. However, there remain a few areas where there appears to be no concensus within the scientific community on standard techniques, as discussed in the following section. Test equipment is reasonably standard in its basic specifications but shows considerable variation in detail between research facilities. This is especially so with instrumentation and data acquisition systems.

3.4.2 Experimental Equipment and Procedures

3.4.2.1 Introduction

Test equipment used by several different investigators for uniaxial and triaxial creep testing are described below. Descriptions are given with as much detail, including load frame and cell capacities, refrigeration methods, instrumentation and data acquisition, as possible.

Most publications with the exception of CRREL do not include detailed test procedures. The majority of the detailed procedures included herein are taken from university theses.

The most detailed procedural reference is given by Vyalov (1965). Although now rather dated, it does document the Russian testing philosophy to that time and is referenced by Schuster (1971), who states that:

> Although there are no generally accepted standard procedures for testing frozen soils, the Russians have done extensive work with frozen soils and have published recommended standard procedures for some of the more commonly used laboratory tests. Their suggested criteria and general test procedures are used, when applicable. However, as their test apparatus is somewhat different, it is generally not possible to make direct use of the exact Rus-

3.4 CREEP BEHAVIOUR

3.4.1 Introduction

Tests for frozen soils in creep and for long-term strength may be conducted with various types of deformations including uniaxial and triaxial compression, uniaxial tension, shear and bending. The majority of researchers prefer the uniaxial creep test because of its simplicity and its potential applicability as a field test. Hence the majority of published creep data involves uniaxial testing. Very limited data exists for creep tests in shear, bending or tension.

The majority of reported testing has been done on man-made rather than natural permafrost samples. Methodologies used in producing artificial permafrost samples are beyond the scope of this report. The final test specimen preparation and testing procedures, however, are similar irrespective of specimen origin.

Many creep tests are performed at temperatures near $0^{o}C$ and accurate and reliable temperature control during long term tests is one of the most critical parameters. The allowable temperature variations when testing frozen soils, as given by Vyalov (1959) are as follows:

Temperature Range	0 to -2°C	-2 to -5°C	-5 to -10°C	Below -10°C
Allowable Variations	± 0.1	± 0.2	± 0.5	± 1.0

The following sections discuss test equipment and procedures in general and include detailed equipment descriptions and procedures developed by several different research groups within about the last ten years. There is general agreement among researchers as to the optimal

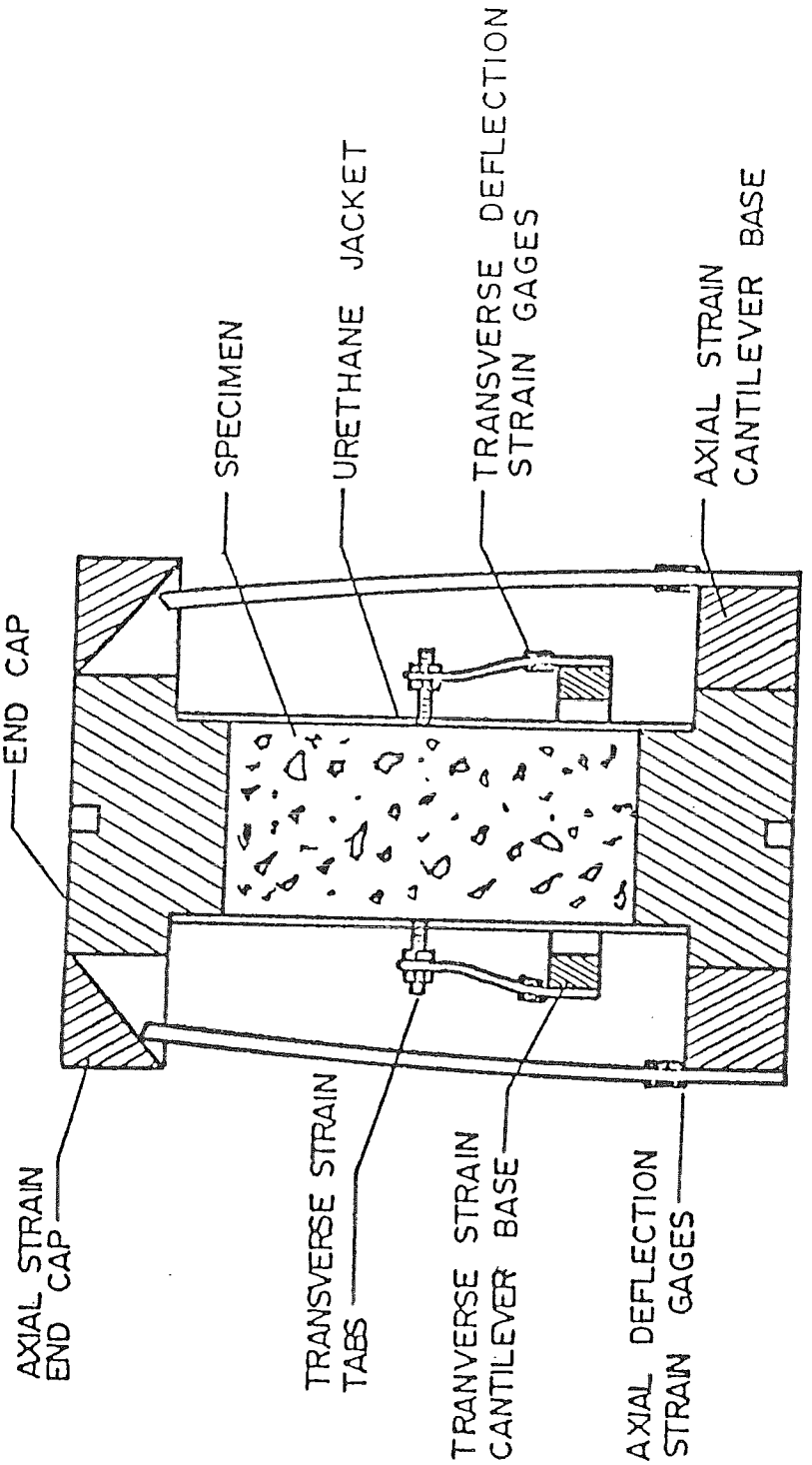
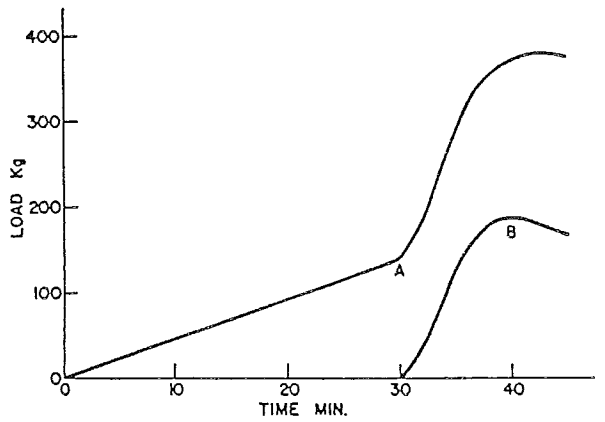


FIGURE 3.3.22 Schematic Drawing of a Specimen with the Axial and Transverse Strain Transducers Attached. (after Simonson and Green, 1972)



NOTE: At point A the piston hits the sample.
B marks the yield point of the sample.

FIGURE 3.3.21 Load-time curve for sample 30-01-76 deformed at -11.7C, $\dot{\varepsilon}$ = 2.6 x $10^{-5}s^{-1}$, at a hydrostatic pressure of 50MNm^{-2}.
(after Jones, 1978)

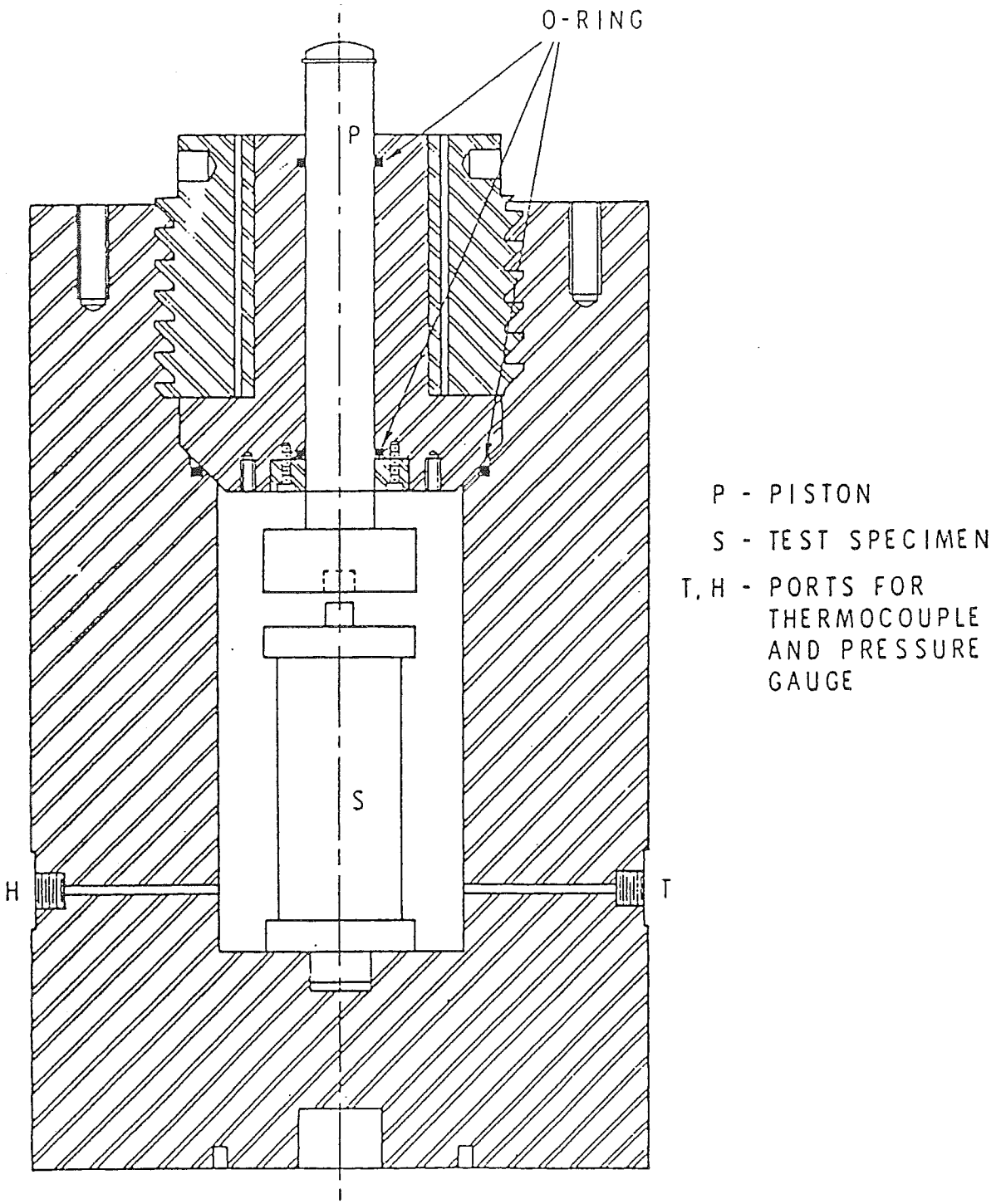


FIGURE 3.3.20 Schematic Diagram of the High Pressure Cell.
(after Baker, et al, 1981)

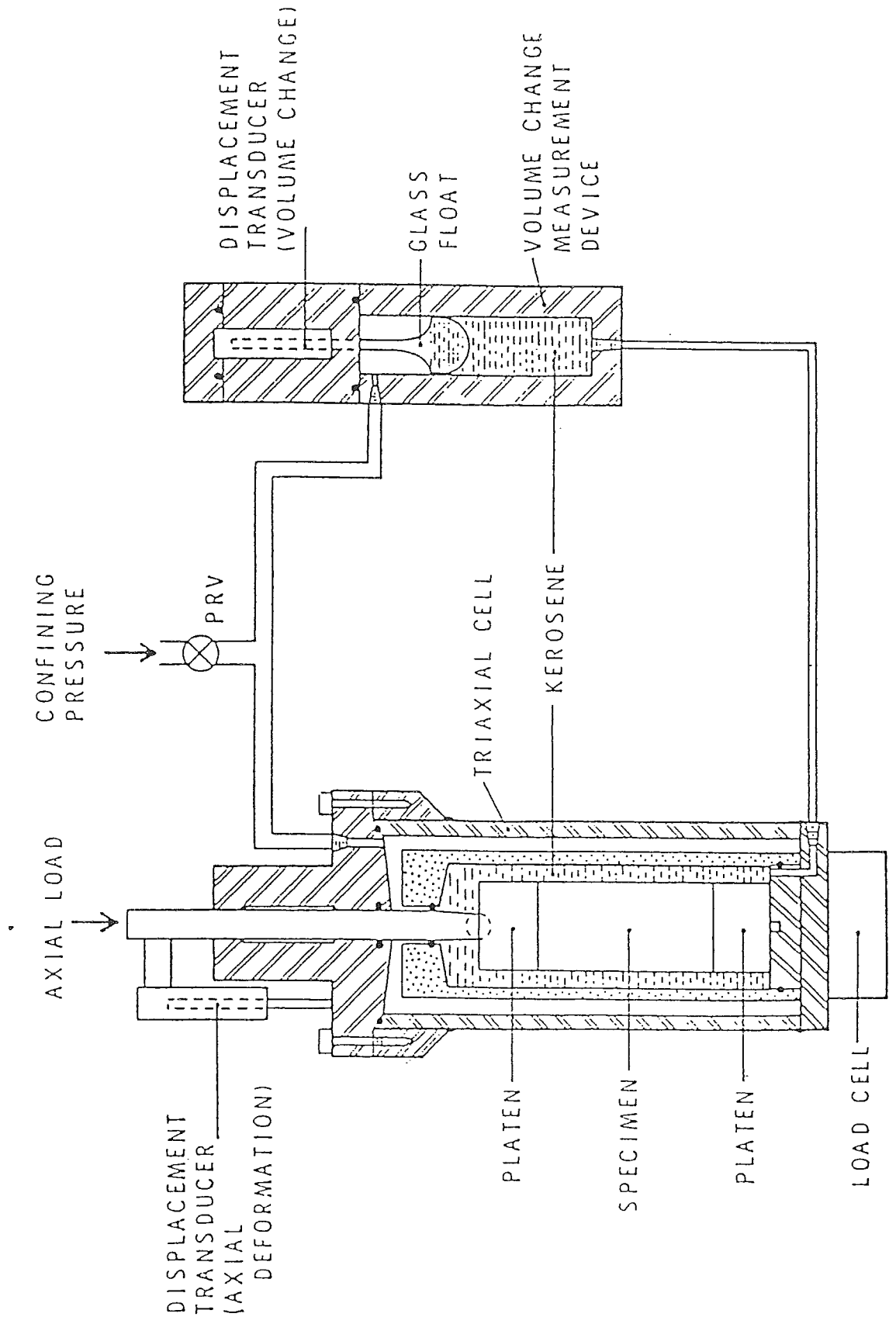


FIGURE 3.3.19 Schematic Diagram of Triaxial Apparatus for Low Pressure Tests. (after Baker, et al, 1981).

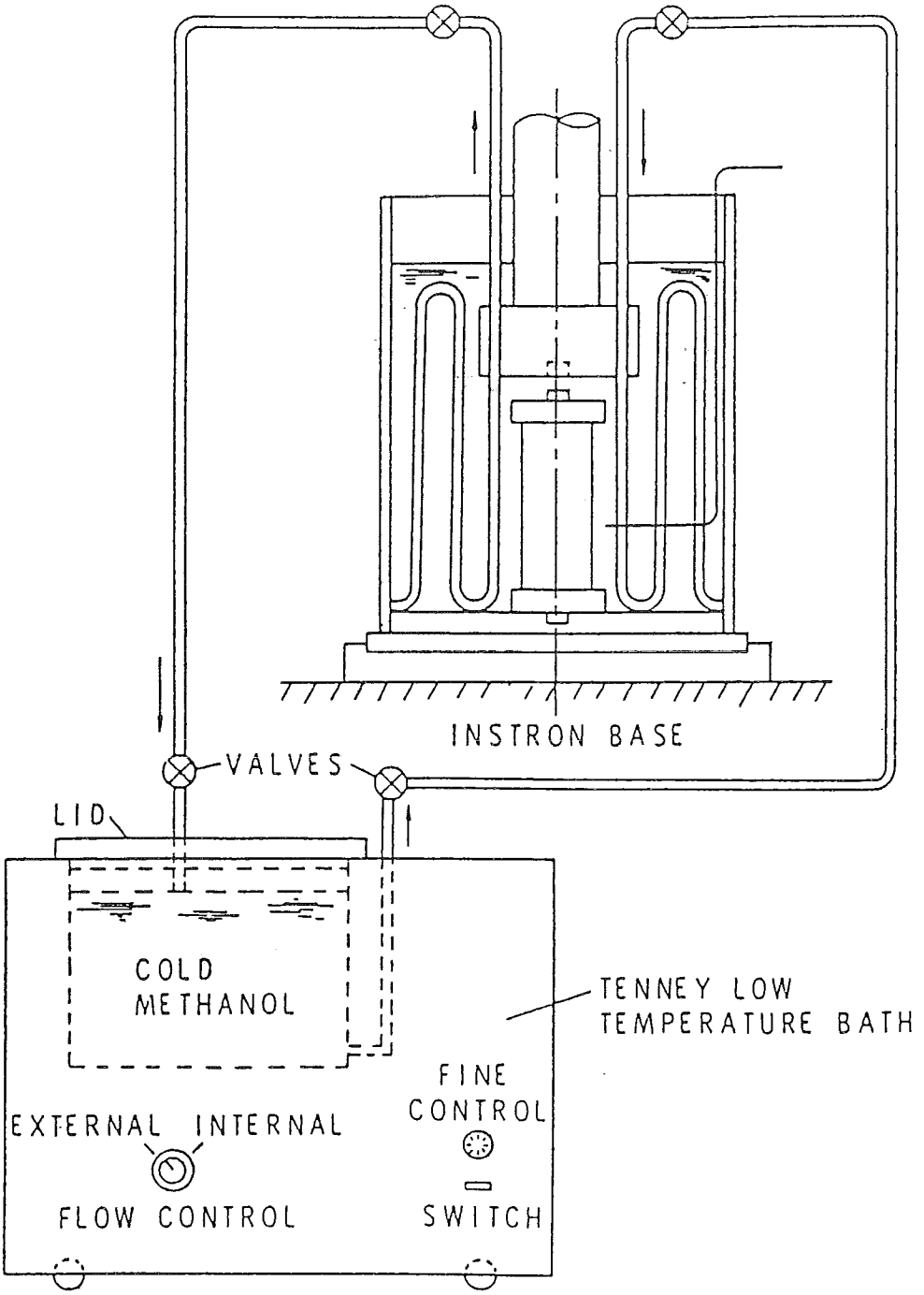


FIGURE 3.3.18 Low Temperature Bath for Unconfined Compression Testing. (after Baker, et al, 1981).

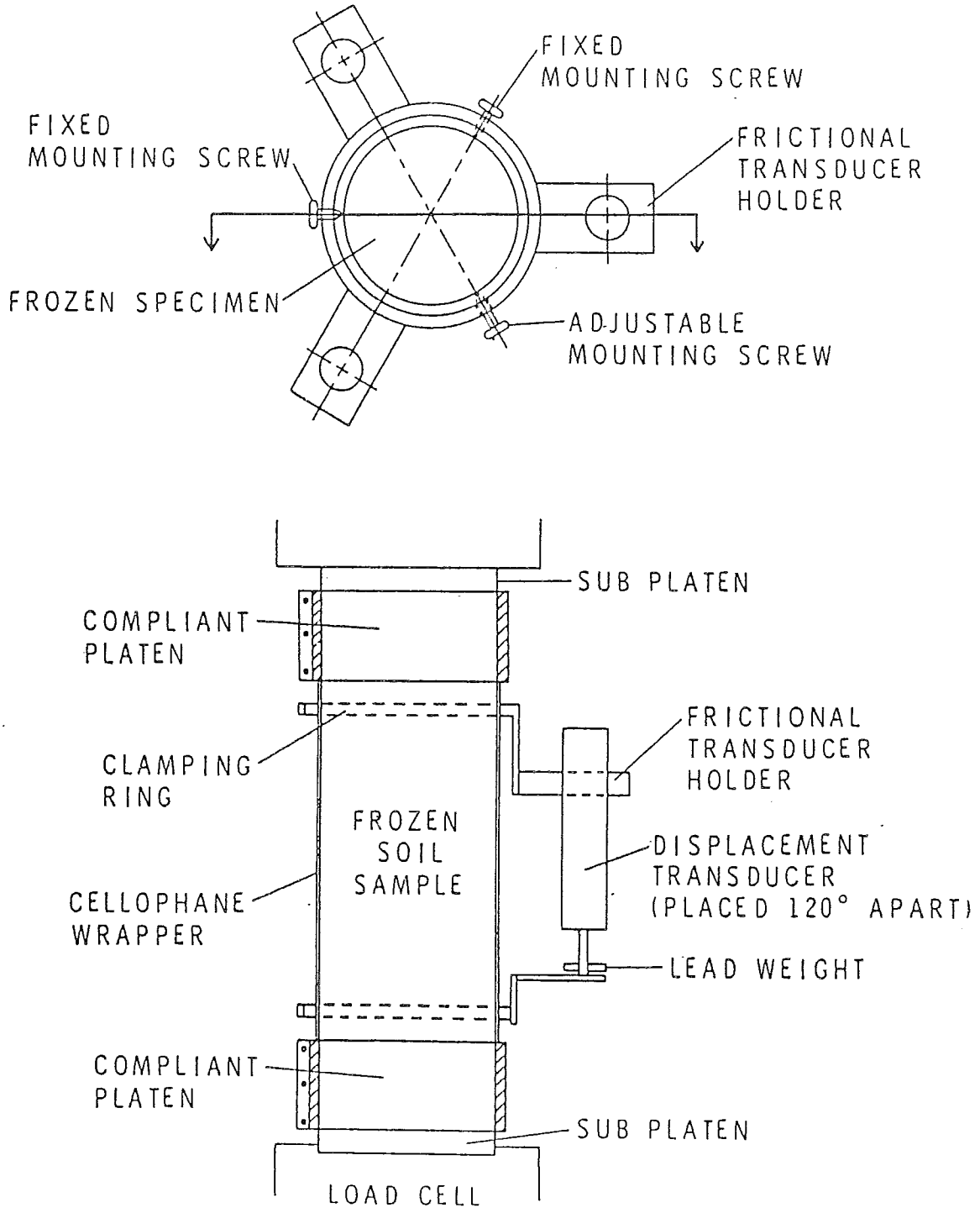


FIGURE 3.3.17 Schematic Diagram of Unconfined Compression Testing Apparatus - Showing Extensometer Mounted on the Specimen. (after Baker, et al, 1981).

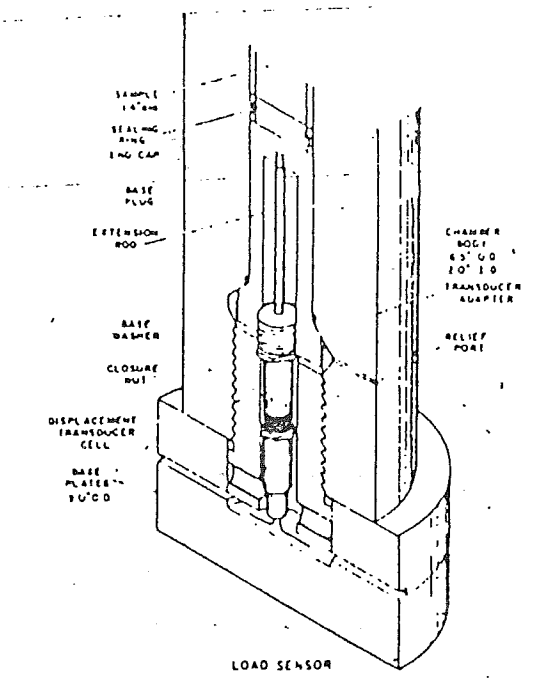


FIGURE 3.3.15 Load Cell (after Chamberlain, et al, 1972)

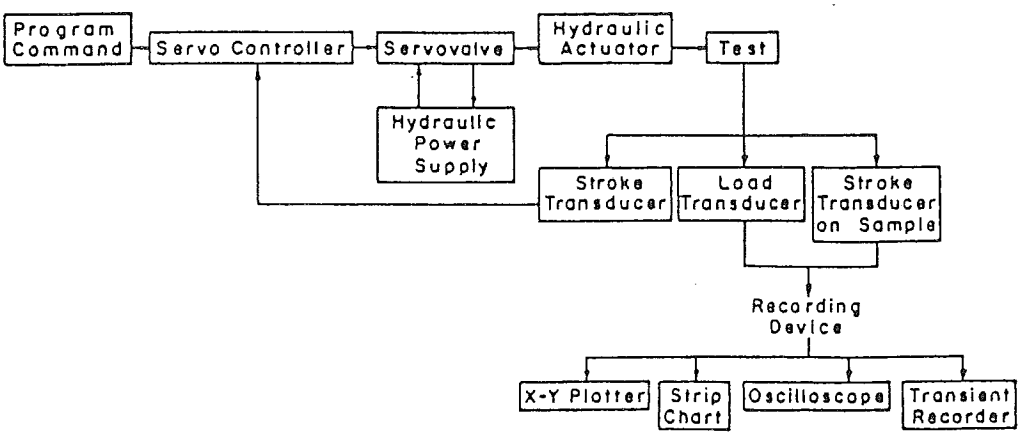


FIGURE 3.3.16 Schematic of Test Setup (after Haynes, et al, 1975).

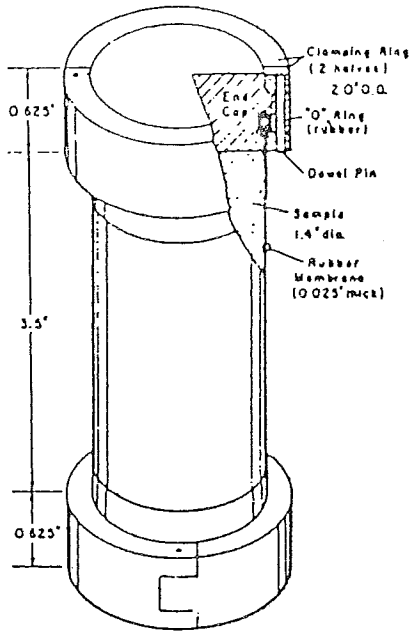


FIGURE 3.3.13 Encapsulated Test Sample (after Chamberlain, et al, 1972).

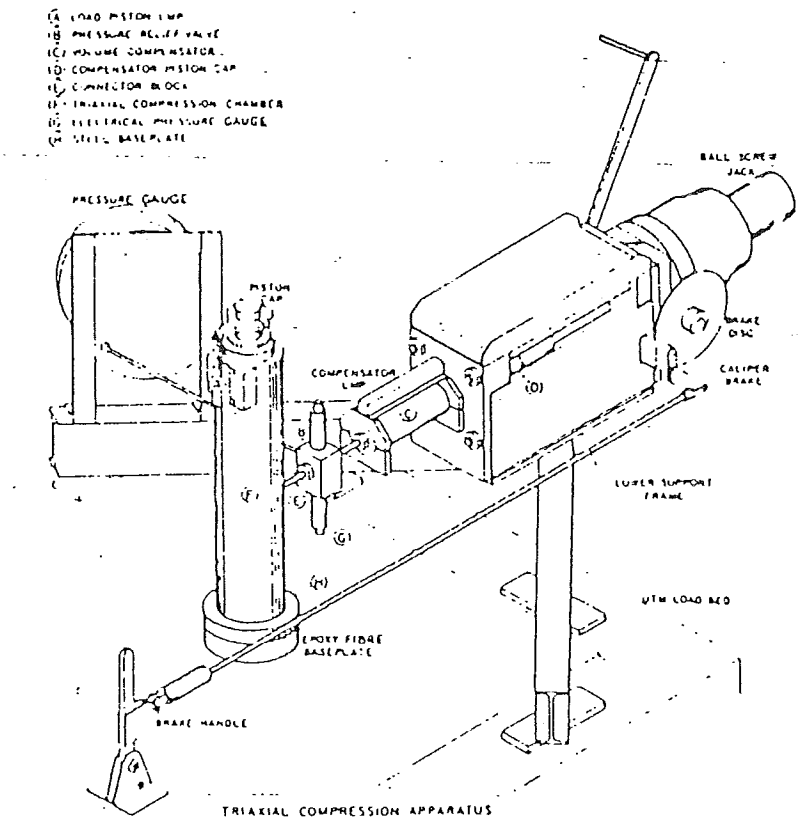


FIGURE 3.3.14 Test Apparatus (after Chamberlain, et al, 1972).

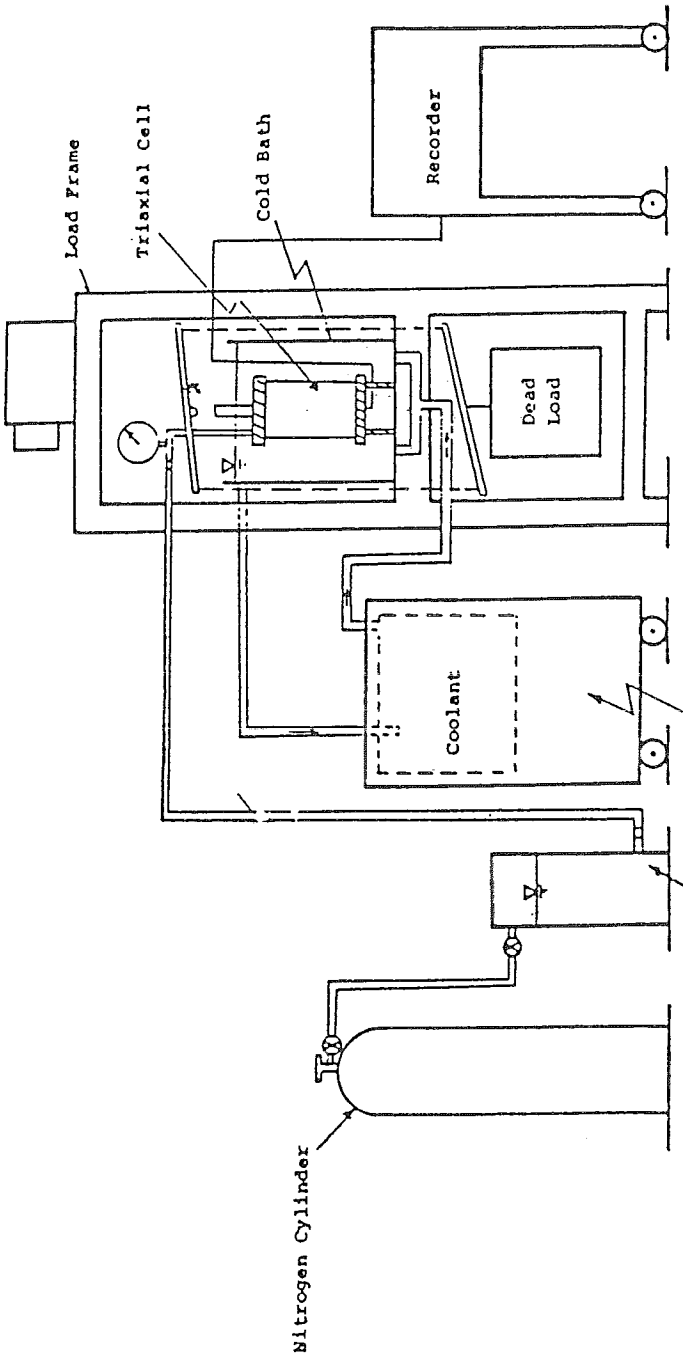


FIGURE 3.3.12 Layout Showing Test Equipment. (after Alkire, 1972)

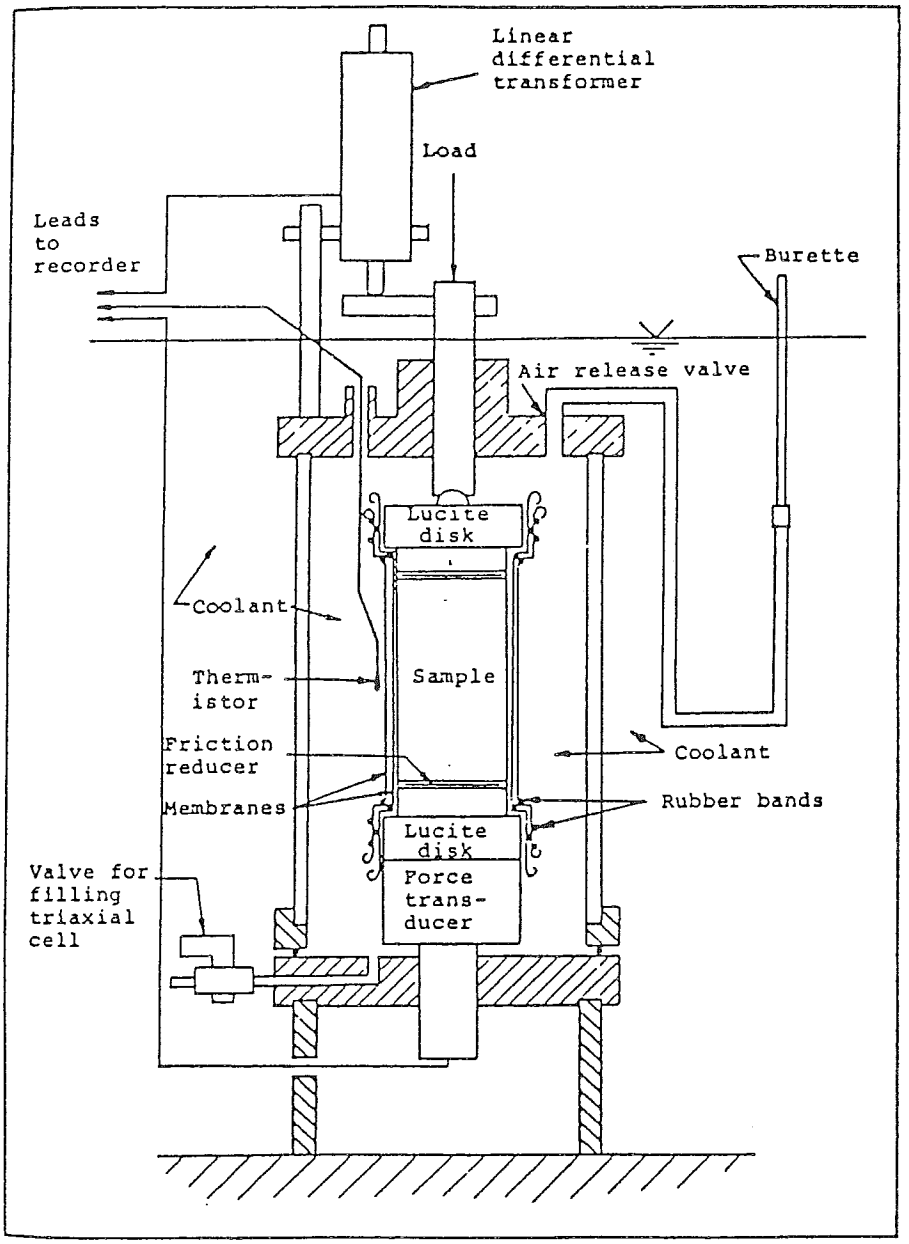


FIGURE 3.3.11 Schematic Diagram of Triaxial Cell Showing Sample Placement. (after Goughnour, 1967)

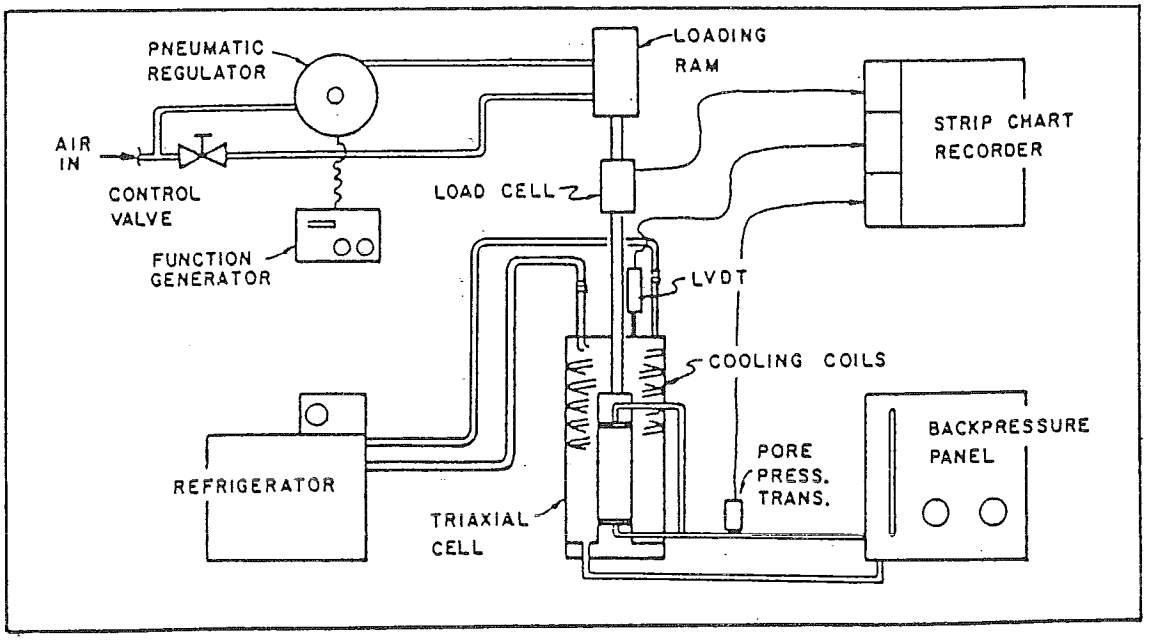
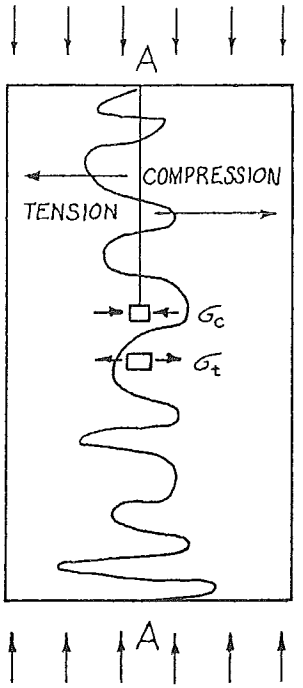
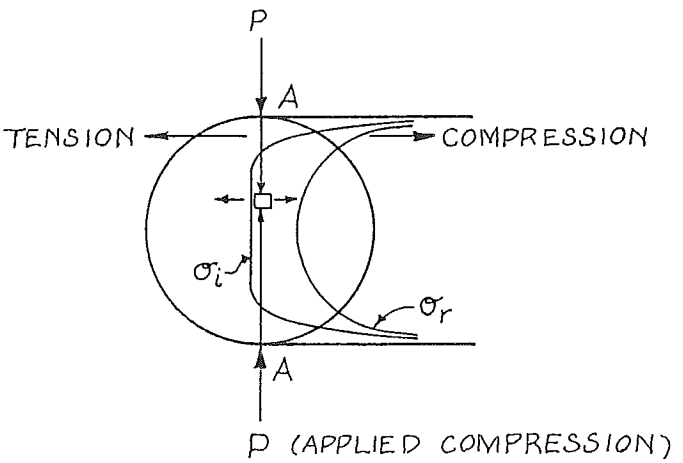


FIGURE 3.3.10 Test Equipment for Freeze-Thaw and Repeated Load Test. (after Alkire and Morrison, 1982)



(a)



(b) STRESS DISTRIBUTION IN THE BRAZILIAN TEST

FIGURE 3.3.9 (after Fairhurst, 1970).

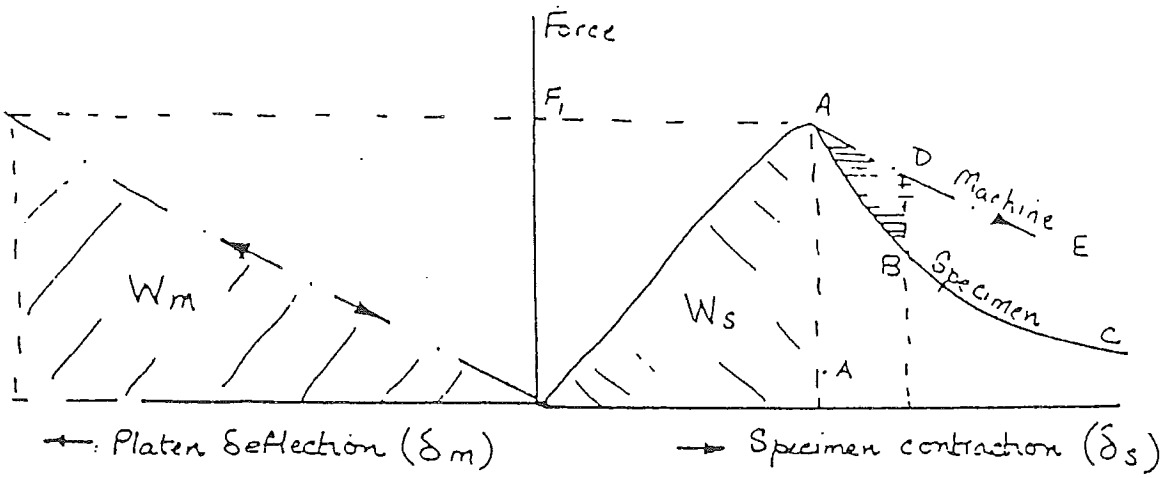


FIGURE 3.3.7 Partition of Energy Input to Loading System.
(after Fairhurst, 1970)

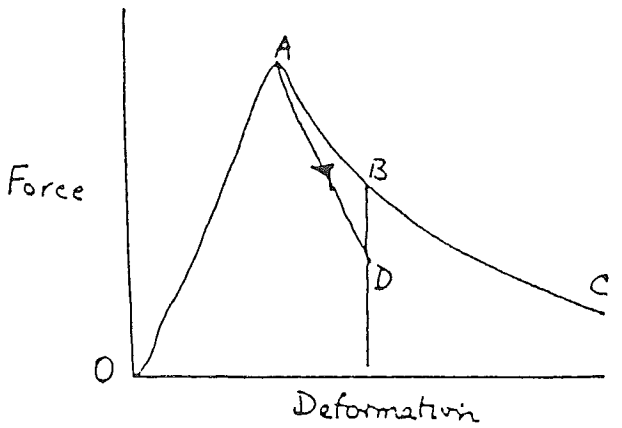


FIGURE 3.3.8 Energy Distribution in a Stiff System.
(after Fairhurst, 1970)

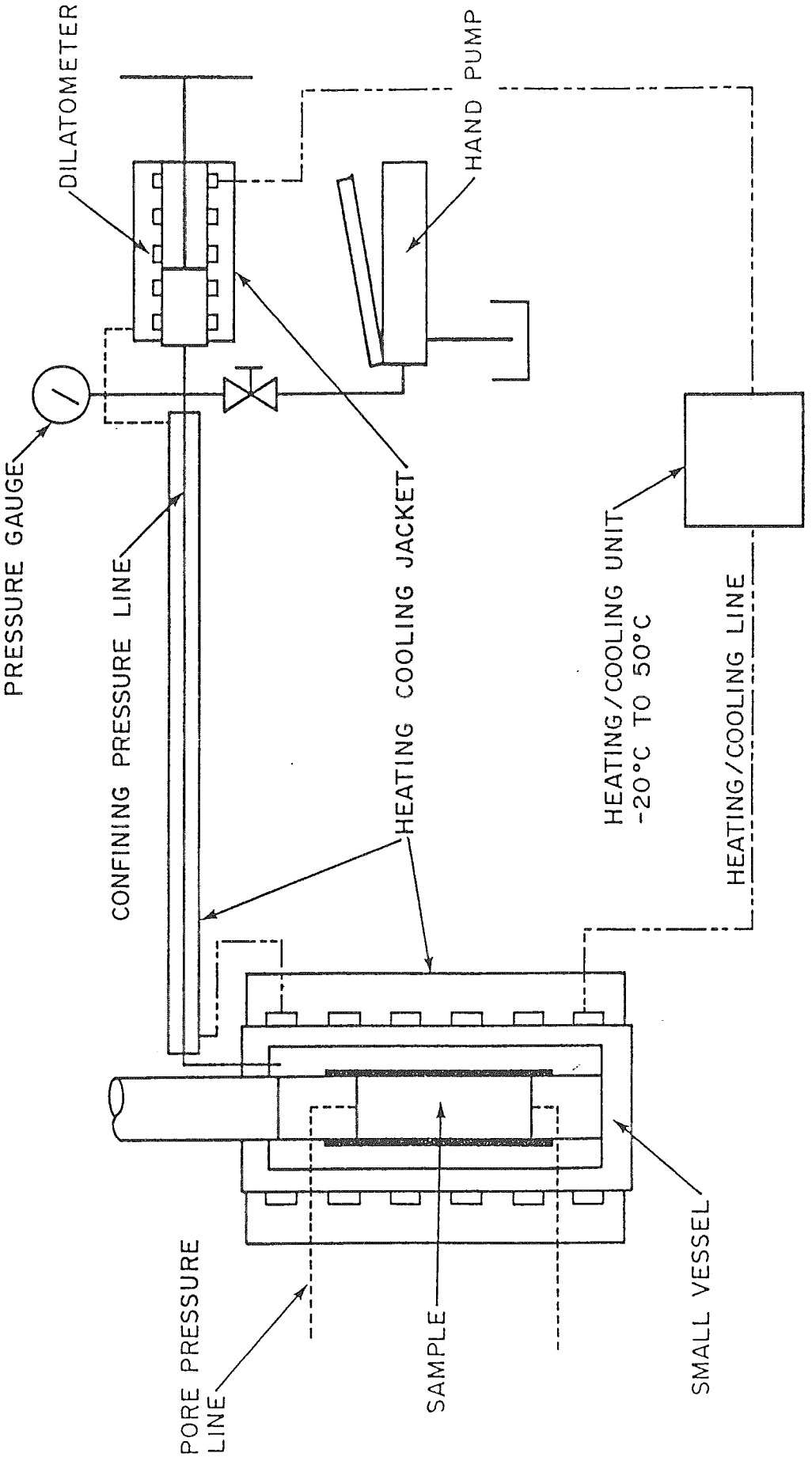


FIGURE 3.3.6 Confining Fluid/Volume Strain Measuring System (not to scale). (Geotech)

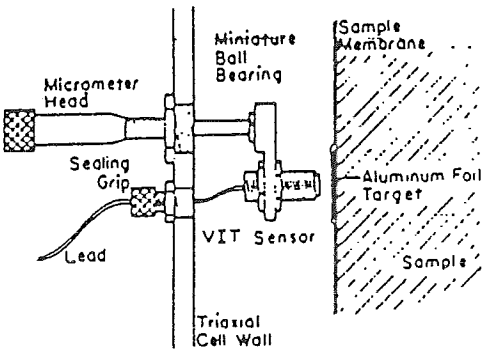


FIGURE 3.3.5 Sensor Mounting Detail (after Cole, 1978)

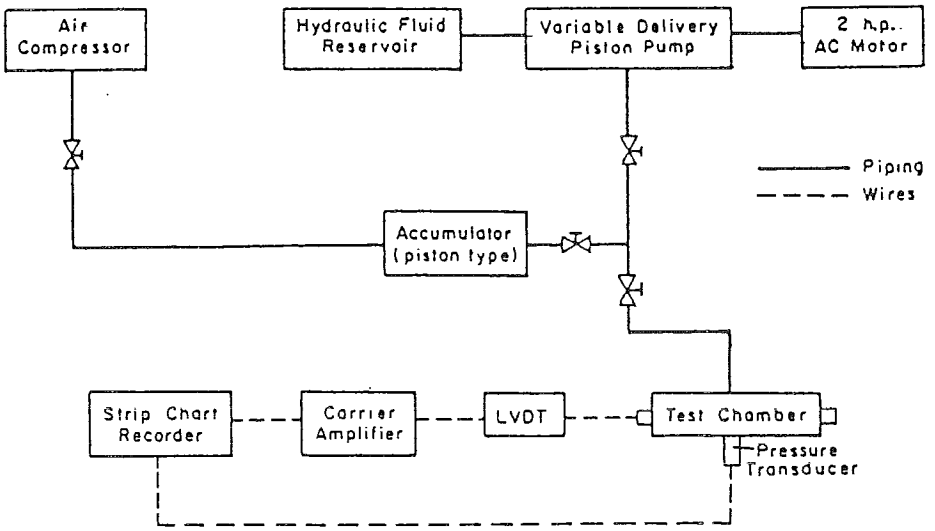
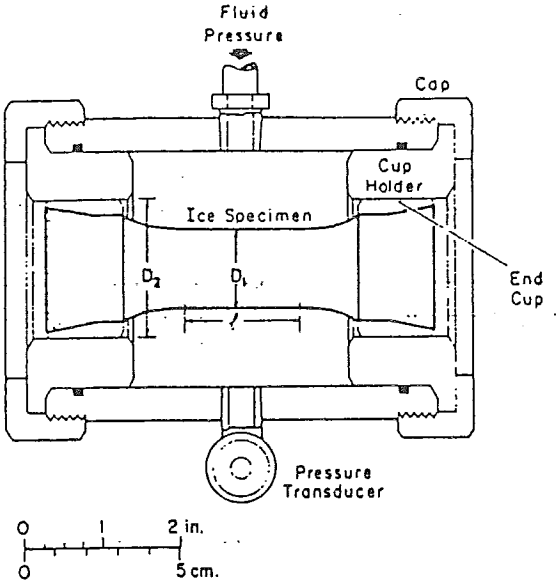
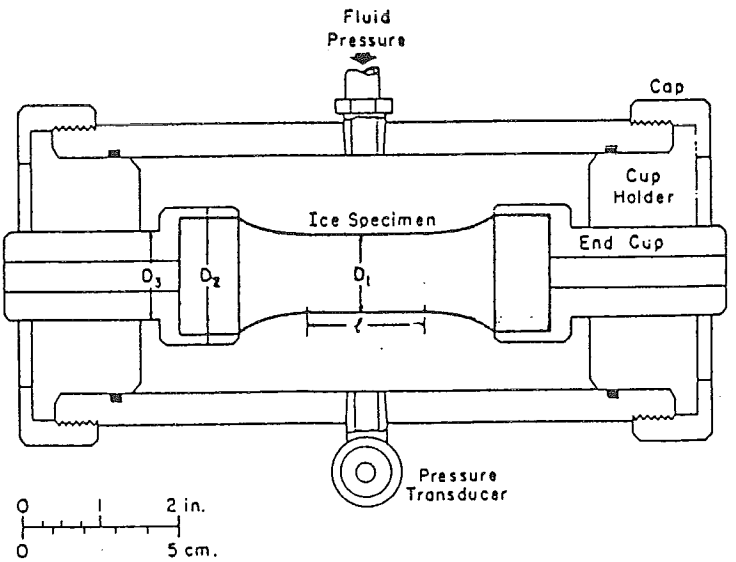


FIGURE 3.3.4 Schematic (after Haynes, 1973)



a. *Series 1 tests.*



b. Series 2 tests.

FIGURE 3.3.3 Test Chambers. (after Haynes, 1973)

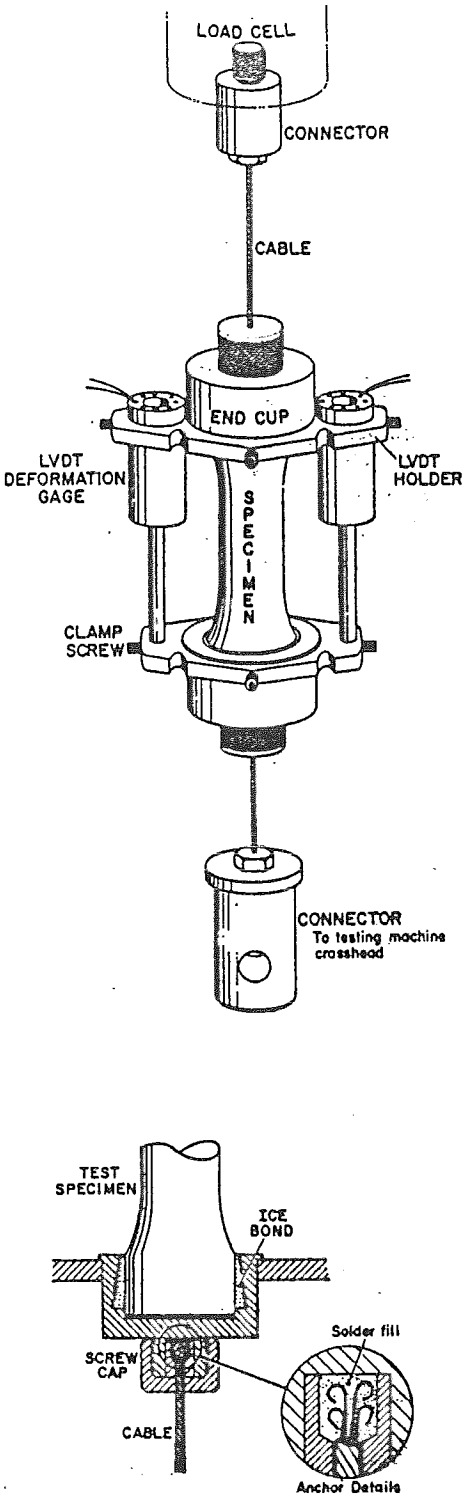


FIGURE 3.3.2 Freezing-in Tensile Testing Arrangement:

(a) pulling systems
(b) connector detail
(after Hawkes and Mellor, 1972)

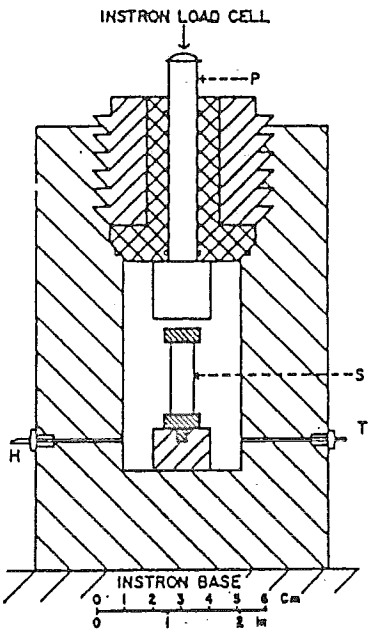


FIGURE 3.3.1 Diagram of the High Pressure Cell (after Jones, 1978)

932-2

TABLE 3.3.1 Test Conditions (after Jessberger and Ebel, 1981)

Compressive strength tests		Creep tests	
Strain rate $\dot{\varepsilon}$	Result	Unconfined compression σ_1	Result
0,02 %/min	σ_{fa}; E_a	$0,4 \cdot \sigma_{fb}$	ε_{fc}; t_{fc}
1,0 %/min	σ_{fb}; E_b	$0,7 \cdot \sigma_{fb}$	

NOTATION: For a better understanding all used terms are listed and indicated.

Compression tests

$\dot{\varepsilon}$	%/min	strain-rate
σ_{fa}	[MN/m^2]	stress at failure related to the test with $\dot{\varepsilon}$ = 0,02 %/min = $3,3 \cdot 10^{-6}$ sec^{-1}
E_a	[MN/m^2]	secant modulus related to the test with $\dot{\varepsilon}$ = 0,02 %/min at 50 % of strength
σ_{fb}	[MN/m^2]	stress at failure related to the test with $\dot{\varepsilon}$ = 1 %/min = $1,7 \cdot 10^{-4}$ sec
E_b	[MN/m^2]	secant modulus related to the test with $\dot{\varepsilon}$ = 1 %/min at 50 % strength

Creep tests

σ_1	[MN/m^2]	constant vertical stress for creep tests
ε_{fc}	[%]	strain at failure according to the inflection point of the ε-t-curve
t_{fc}	[h]	time at failure according to the inflection point of the ε-t-curve

not be necessary for normal tests but where the sample length is inadequate frictionless end platens are logical since one really only has an index test anyway.

Sayles further states that proper sample preparation and test temperature control must be emphasized. Erratic test results often result from improper temperature control. Sayles recommends that above 25°F (-3.9°C) the test temperature should be maintained within 0.1°F and preferably within .05°F. Rapid circulation liquid systems are now generally used for temperature control and Sayles notes that it is generally better to use a heating system, (rather than cooling), to control temperature.

With sample preparation Sayles emphasized the importance of obtaining the correct density prior to testing and of checking the density again after testing. For undisturbed samples he recommends that they are trimmed on a lathe after coring and that the ends are carefully trimmed to obtain a right cylinder. The cuttings can be used to obtain water contents. Also each sample should be photographed after testing.

Mr. S. Green of Terra Tek Inc., (personal communication, 1983), also stated that he did not believe that factors such as machine stiffness, compliant platens, etc., would, in most cases, be of significance because of the generally ductile nature of frozen soil behaviour.

visible evidence of major structural disintegration, at least until the deformation has reached an advanced state. Such behaviour is usually referred to as 'ductile' or 'plastic' deformation.

When loads are applied very rapidly, as in impact situations, the observed response is often quite different. The material shatters, and the fragments are rapidly ejected from the point of impact with relatively little prior deformation. This type of behaviour of the material is loosely referred to as 'brittle fracture'.

Mr.M.Jefferies, Gulf Canada Resources (personal communication,1982) noted that in any strength testing it is imperative to obtain very accurate diametral strain along with axial strain data in order to assess the true constitutive material behaviour. Otherwise, one must make an assumption, (e.g. no volume change), in which case very sophisticated mathematical modelling is probably not warranted. The author is in agreement with Mr.Jefferies on this.

Jefferies further questioned the value of laboratory short-term strength tests. He preferred to use a field pressure probe and the resulting rebound modulus or else elastic properties derived from field geophysical techniques. As pointed out by Fairhurst (1970), however, there are areas where short term laboratory deformation test data is applicable and these should not be overlooked. It is the authors' opinion that the standard test procedures recommended by the I.S.R.M. and I.A.H.R. for rock and ice respectively, provide a sound basis for a standard for short term deformation tests for permafrost. The use of end cap lubricants should not be allowed because tensile failure may be induced. Finally, if brittle behaviour is anticipated, (e.g. cold permafrost and/or high loading rates), the overall test system stiffness should be considered as it may affect the ultimate material constitutive behaviour.

Mr. F. Sayles (C.R.R.E.L) (personal communication, 1983) notes that most frozen soils are not truly brittle and one can compensate for the compliance of the test equipment. He states that compliant platens may

(iv) Data Analysis

From the compression tests, the strength, the strain at failure, and the secant modulus E are obtained. The secant modulus is calculated at 15% of stress at failure.

In case failure has not been reached in the test, the stress at 15% deformation is taken as the strength.

From the creep tests the strain at failure ϵ_{fc} and the corresponding time t_{fc} are obtained at the inflection point of the ϵ-time curve. These quantities may be found from the $\dot{\epsilon}$-t curve.

(v) Additional Soil Classification

The soil under investigation should be classified according to the Unified Soil Classification System as modified for frozen soils (MIL-SED 619B, 12 June 1968, USA CRREL Technical Report 150, August 1966, or Technical Memorandum 79 NRC 75/76). As a minimum the gradation curve, moisture content, liquid and plastic limits, degree of saturation, density, and salinity, if relevant, of the soil samples should be documented.

3.3.6 Discussion

It is evident from the above discussion that brittle behaviour of frozen materials is poorly understood. Friction reducers and compliant platens, used by many researchers in the past, may lead to erroneous interpretations of the true material behaviour that may adversely influence research into problems in drilling, excavation, etc. This area deserves further study before standard test procedures can be evolved.

Fairhurst (1970) notes that:

> Many of the activities, e.g. erection of buildings,and roads, use of freeezing techniques in shaft sinking, involve consideration of the long-term (i.e. slow) mechanical response of frozen ground to loading. This has been studied relatively extensively. In other situations, principally those involving fragmentation of the ground (drilling, tunnelling, ripping, and blasting), the short term response is of dominant concern. Study of this short-term behaviour has been almost totally neglected, due in part, no doubt, to the greater complexity of experimental tests thought to be necessary to define it. Slow deformation is usually accompanied by little if any loss in load bearing capacity, and no

procedure of sample preparation and freezing, including thermal history of undisturbed frozen samples.

(iii) Test Conditions of Reference Tests

In addition to, or included in the individual tests program, 4 reference tests should be performed with respect to unconfined compression: two compressive strength tests with slow and fast strain-rate, respectively; and two creep tests, the constant axial stress being related to the unconfined compresssive strength (see Table 3.13 and Notation).

All reference tests should be performed at a constant temperature of $T = -10° \pm 0.5°C$. The slenderness ratio should be $h/d = 2/1$ with a minimum diameter of 5 cm. As mentioned before, full end friction should be maintained.

Being aware of the influence of the stiffness of the testing machine on the results of the compression tests, it is proposed to use a test machine with a load capacity of at least 100 kN.

The testing machine should provide a strain-rate control system. The plate velocity can be controlled in such a way that the strain-rate $\dot{\varepsilon}$ is constant. this may be done by measurements performed by an extensometer attached to the specimen. The applied load should be measured by a load cell of adequate capacity in order to provide sufficient resolution of the results.

The compression test should be performed to a minimum strain of 15% in which the state of failure should be reached for most frozen soils. However, failure may not be reached at 15% strain in frozen clay samples. According to the strain-rate the duration of the fast test will be 15 min whereas the duration of the slow test will be 12.5 h.

Assuming no volume change, the cross-sectional area F' of the sample at the vertical deformation Δh can be calculated from:

$$F' = \frac{V}{h_0 - \Delta h}$$

where h_0 = initial height, and V = initial volume. The duration of the creep tests should be at least one day for the test with high load and 3 days for the test with low load.

frozen soils, but the chosen test conditions should be as close as possible to those used in common practice of testing frozen soil. Because the reference tests do not meet all demands, in many cases it can be necessary to perform the reference tests in addition to other project-related tests.

(ii) Sample Preparation

The reference tests will be performed on cylindrical soil samples. The samples are prepared as undisturbed frozen samples or as undisturbed or disturbed unfrozen samples, which are frozen after moulding.

Frozen samples are drilled on site or in the laboratory out of a frozen block, in both cases by means of a core auger bit with adequate inner diameter. Specimen ends must be plane and parallel within close tolerances. Sample coring and preparation have to be done in a room with negative temperatures to prevent melting of the sample.

Unfrozen undisturbed soil samples are prepared as conventionally done in soil mechanics, whereas the preparation of disturbed specimens needs special regulations. Unfrozen samples of cohesive soil are formed in a steel mould or plastic mould. The soil with the desired moisture content can be densified to the desired density by a hydraulic compression apparatus or by a miniature compactor.

Cohesionless dry soil is rained into a mould with appropriate dimensions. The desired density can be achieved by use of a vibrator table or by a suitable raining height. After preparation the soil sample has to be watered or saturated by methods usually used in soil mechanics.

The undisturbed or disturbed unfrozen samples are frozen quickly in such a way that the frost can penetrate from all sides into the sample. This can be done in a cold room, cold chamber or triaxial cell with circulating brine. The temperature should be at -10°C. During freezing the endcaps should be frozen to the soil samples to achieve defined end conditions. After freezing the sample has to be stored in a freezing chamber that has only small temperature fluctuations to minimize thermal disturbance as the compressive behaviour of frozen soil is greatly affected by temperature and by temperature fluctuations. The reference tests have to be performed within one week after the freezing of the samples is completed.

For correct interpretation of the results of the reference tests it is necessary to describe as precisely as possible the

A load cell and a manganin wire pressure coil were also designed, assembled and calibrated. The pressure coil consists of 350 manganin wire wrapped around a spool machined of plexiglass. A protective covering was also made to prevent inadvertant damage to the windings. The pressure coil was calibrated to 100 ksi using a Heise pressure gauge as a secondary standard. Pressures are measured accurate to within ±5 bars.

The load cell was made in the shape of a hollow cylinder with one end solid for loading. Strain gauges bonded to the walls of the load cell are wired into a four-arm strain gauge bridge in such a manner to cancel out any bending which might occur. This load cell will be used in the unconfined compression tests and the confined triaxial tests where the strain-rates are less than about 10^{0}/sec. It is tentatively planned that strain gauges bonded directly to the specimen will provide the necessary output for the higher strain-rate tests conducted on the gas gun. The load cell is accurate to ±.5 bar stress on a 2-inch diameter sample.

All transducers are located within the pressure vessel. This technique eliminates such problems as seal friction effects, hydraulic line loss in pressure and deformational effects of the loading piston which are usually encountered in external measuring equipment.

3.3.5 Proposed Method For Reference Tests on Frozen Soil - After H.L. Jessberger and W. Ebel (1981)

(i) Introduction

Today the number of laboratories which investigate frozen soils is increasing. In order to make the exchange of knowledge and experience within the scientific community easier and to enable a comparison of data regarding the mechanical behaviour of frozen soils, the following proposal is presented. The basic idea is the introduction of reference tests for the identification of frozen soils.

Two unconfined compression tests and two uniaxial creep tests are chosen as reference tests. The compreession tests performed with different strain rates lead to compressive strength and modulus of deformation. The creep tests are introduced because the creep behaviour of frozen soil can be important depending on the magnitude and duration of loading. It is intended to use the results of the reference test, showing typical properties of frozen soils, for identification. It should be emphasised that the proposed test method is not a standardization for testing of

Apparatus

A 2 kilobar pressure vessel, including all necessary loading pistons, base plugs with electrical lead throughs, high pressure fittings and pressure seals was designed to accommodate 2-inch diameter by 4-inch long specimens. The loading pistons are specially designed for use in the split Hopkinson bar gas gun and a 140 kip servo-controlled hydraulic loading press. The hydraulic press was used to perform the controlled loading path tests and the low strain-rate tests (10^{-4}/sec to 10^{0}/sec) while the split Hopkinson bar was used for the high strain-rate experiments.

The 2 kilobar pressure vessel has a water jacket enclosing the entire vessel and is sealed at both ends with O-rings. Coolant from the refrigeration unit circulates through the water jacket and around the pressure vessel walls to maintain the vessel at the desired testing temperature. A 2.5 inch urethane foam thermal insulation layer was added to the pressure vessel to reduce the convective heat transfer. An iron-constantan thermocouple placed inside the pressure vessel is used to monitor the confining fluid temperature and provide feedback control for a digital temperature indicator and controller. Two digital comparators are used in conjuction with the temperature indicator to turn the liquid coolant pump on and off depending on temperature limit set in the comparators. The pressure vessel can be maintained to within $\pm 2^{o}$F of the operating temperature.

Axial and transverse strain transducers were designed, assembled and calibrated for use with the 2-inch diameter by 4-inch long frozen material specimens. The axial strain transducers consist of four cantilever arms mounted on a base ring which may be firmly attached to but easily removed from the hardened steel specimen end caps. These cantilever arms extend the entire length of the specimen and contact a conically tapered ring attached to the opposite loading end cap. Any axial strain on the specimen is recorded as bending strain in the cantilever arms. Strain gauges bonded directly to the cantilever are wired into a four-arm strain gauge bridge to provide the output. The transverse strain is measured in a similar manner. Four cantilevers attached to a steel ring about the specimen form two sets of orthogonal transverse strain indicators. Transverse displacement within the specimen are transferred into bending strain in th cantilever by means of screw adjustable contactor points which rest on the surface of the specimen. Figure 3-13 shows a schematic drawing of the transverse and axial strain transducers attached to a specimen. Transducers of this type are capable of measuring large deformations (30% axial strain and 15% transverse strain) with an accuracy of 10% strain $\pm$.01% strain.

capacity were used throughout the experimental program and were chosen to match the expected sample failure load. The temperature of the triaxial cell fluid was measured using a temperature measuring probe located at the mid-height of the sample between the sample and the copper cooling coil. This probe was constructed using a stainless steel tube and an Atkins No.3 thermisotr bead (Roggensack, 1977). The thermistor was calibrated using a quartz thermometer to $\pm 0.001^{o}C$ and therefore, measured a temperature to $0.01 \pm .005°C$.

B. Test Procedure

The cell and sample were transferred from the soil preparation room to the cold room that contained the constant displacement rate loading frame. The cooling coils were connected to the constant temperature circulation system. The ethylene glycol at a temperature of $-7^{o}C$ was circulated through the cell for 24 hours to bring the sample to test temperature. The temperature measuring probe was inserted into the cell between the cooling coil and the sample and the temperature was monitored.

Once the sample temperature had stabilized the LVDT and load cell were adjusted to their zero reading. The gearing system of the constant displacement rate press was adjusted to the desired rate, a small seating load was applied and the electronic recording system was started. Throughout the application of constant deformation rate the load, the vertical deformation, and the temperature were monitored at regular time intervals. The electronic output data was recorded on a magnetic tape and subsequently transferred to a central computer for data reduction and plotting.

3.3.4.10 Testing by Terra Tek Inc., Salt Lake City,Utah (After Simonson and Green, 1972

Testing was done to develop constitutive equations for frozen geologic materials for use in shock and structural code calculations. Emphasis was on the effect of strain rate on the pressure-volume strain at various confining pressures for three frozen materials prepared by CRREL. The triaxial compression strain-rate data will be supplemented by a variety of controlled quasi-static loading and unloading conditions including J_1 = constant, $\sqrt{J_2}$ = constant, proportional stress and uniaxial strain tests.

from the upper end cap. The temperatures of the sample and the refrigerant fluid were continuously monitored. The samples were tested over a temperature range from -0.55° to -5.56° C (to 22°F).

3.3.4.9 Testing at the University of Alberta

Constant strain rate tests were performed at the University of Alberta by Sego et al (1982) on man made frozen saline sand samples. Equipment and procedure description, (after Sego et al,1982), are given below. The triaxial cell used is the same as used by Savigny (1980) for creep tests and is described in detail later in this report.

A. Test Equipment

The tests were performed using a 90 kN capacity Wykeham-Farrance constant displacement rate loading press. The displacement rate could be varied between 1.2 mm per minute and 0.00049 mm per minute.

The triaxial cell, which was modified to provide temperature measurements, was selected since it allows a cell fluid to surround the sample hence reducing ablation of the pore ice during testing. This light paraffin oil also acted as thermal mass surrounding the sample which helps to maintain a constant temperature in the sample during the experiment.

The temperature of the sample was maintained constant by circulating a mixture of ethylene glycol through the cooling coils that surround the sample. The cooling coils which act as heat exchangers are mounted within the triaxial cell. The temperature of the ethylene glycol mixture was maintained constant during the experiment by circulating the fluid through a Hot Pak constant temperature bath. The base of the triaxial cell was isolated from the load frame by a cooling plate mounted between the cell and the movable loading frame platen. The cooling fluid from the Hot Pak apparatus was circulated through this plate. The triaxial cell and measuring equipemnt were housed in an insulated cabinet which isolated them from the temperature fluctuations of the cold room.

The measuring instruments were a linearly variable displacement transducer (LVDT), thermistor, and temperature compensated strain gauge load cell. The Hewlett Packard 24 DCDT LVDT was capable of measuring deformations to .0013 mm. Load cells of various

3.3.4.8 Testing at the University of Alaska

Unconfined compression tests on fine grained natural permafrost samples at warm temperatures ranging from -5.56°C to -0.55°C were done at the University of Alaska. Test procedure and equipment description are given below (after Phukan,1980).

The samples selected for the tests were Fairbanks Silt which had a specific gravity of 2.56 (low due to organic content). The preparation of samples for the testing was a careful, detailed process accomplished in the following steps:

1) The cores were cut into a sample size approximately 6.4 cm diameter x 9.1 cm length with a length to diameter ratio between 2 and 3. A miter box and a hack saw were used to make the cuts as well as to get the ends parallel.

2) A 0.16 cm diameter hole was drilled to about 3.8 cm deep into the bottom of the sample for later insertion of a temperature probe.

3) To ensure a correct size, dust caused by sublimation (if any) was carefully scraped around the sample and the weight was recorded. Also, the initial height and diameter were noted.

4) Trimmed sections from the end of samples were used to determine water content of samples.

5) A thin flexible rubber membrane was then placed over the sample to protect it from sublimation and from the cold chamber fluid coming in contact with the sample. The sample was then ready for testing.

All specimens were tested in a modified triaxial cell on an electrohydraulic machine. A copper coil was installed in the cell to circulate coolant fluid around the sample from a refrigerating unit and the chamber was filled with a mixture of cold antifreeze and water. From a test with the thermocouple placed in the sample, it was determined that the sample reached a particular temperature throughout its mass after being conditioned in the test chamber. The machine has an automatic loading system by which different strain rates can be applied to the sample. Tests were conducted under a constant strain rate of 5% strain rate per minute. The axial deformation of the samples was recorded with a sensitive dial gauge (10^{-4} in reading)

as the piston descended, the volume of the cell was decreased and the hydrostatic pressure was, thus, increased. Typically, the hydrostatic pressure rose by 1 MNm^{-2} during an experiment. The output of the Instron load cell, therefore, was a linearly increasing load due to the increasing hydrostatic pressure plus the load-time curve of the ice sample itself, as shown in Fig.3-12.

The linear, hydrostatic, part of the curve was extrapolated and subtracted from the curve to give the load-time curve of the ice sample alone, as shown in the lower part of Fig.3-12. The hydrostatic pressure was also monitored independently with a Heise gauge, and this confirmed the linear increase in pressure. The load-time curve was then converted to stress-strain in the following way. The load, F, was converted to stress, σ, using the equation

$$\sigma = \frac{F}{A} \cdot \left(\frac{\ell}{\ell_o}\right)$$

where ℓ was the length of sample and ℓ_o was the initial length of sample. The factor (ℓ/ℓ_o) took account of the increase in cross-sectional area of the sample as the compression took place.

The Instron compressed the ice at a constant speed of deformation. The time axis of the Instron strip chart recorder was, therefore, taken to be directly proportional to the amount of compression, $\Delta\ell = \ell_o - \ell$. The true strain, $\Delta\ell/\ell$, (not ℓ_o) was then calculated.

For most tests the samples were immersed directly in the silicone fluid, without covering them first with a thin rubber sleeve. Some were protected from the oil by such a sleeve but these showed no difference in yield or fracture stress from the unprotected samples. Further tests were done at one atmosphere pressure, using an air bath rather than the silicone fluid, both with and without rubber sleeves, and these tests also showed no significant effect of either the oil or the rubber sleeves.

The application of the hydrostatic pressure raised the temperature of the oil and hence the ice by several degrees. Therefore, two precautions were necessary. The first was to make sure that the temperature never rose above the pressure melting point, and the second was that the temperature had to be allowed to equilibrate after applying the pressure.

The apparatus used in these low pressure tests is shown in Figure 3-10.

Tests were carried out at strain rates between 10^{-6} and 10^{-4} sec^{-1}, at a temperature of $-6^{o}C$.

High Confining Pressures (σ_3 = 0 to 76 MPa)

Triaxial tests at high confining pressures were carried out in a high pressure cell having a wall thickness of 100 mm and internal dimensions of 100 mm diameter and 250 mm height. A schematic diagram of the cell is shown in Figure 3-11. The pressure vessel was surrounded by an environmental chamber maintained at $-10 \pm 1^{o}C$. Most of the tests were carried out at a strain rate of about $7.7 \times 10^{-5} sec^{-1}$. Dow Corning silicone fluid 200 was used as the pressurizing medium. Tests were carried out in a closed system. An initial hydrostatic pressure was applied to the specimen and as the piston was forced into the cell the hydrostatic pressure, σ_3, was increased. No volume change measurements were made.

Additional high confining pressure tests carried out by Parameswaran (1980), and Parameswaran and Roy (1981), included tests at strain rates varying between 10^{-7} and 10^{-2} sec^{-1} and temperatures of $-2^{o}C$, $-6^{o}C$, $-10^{o}C$, $-15^{o}C$, and $-30^{o}C$.

Detailed test procedures are taken from Jones (1978):

The mechanical testing apparatus used is shown in Fig.3-11. The ice sample, S, was placed in a cell capable of withstanding at least 100 MNm^{-2} hydrostatic pressure. The pressurizing fluid was Dow Corning Silicone fluid 200, hand-pumped through the line, H. A piston, P, sealed by two O-rings, applied a uniaxial compressive force to the sample. The whole sat inside a cold box on the base of a model 1116 Instron mechanical tester. All the tests reported here were done at $-12 \pm 1^{o}C$, the temperature usually varying less than $0.1^{o}C$ during a test, as monitored by a thermocouple (T, Fig.3-11) inside the cell. The Instron loadcell, being outside the high pressure cell, measured not only the uniaxial load applied by the crosshead, but also the force of the hydrostatic pressure on the piston, P, and any frictional force of the piston itself. The friction was small and was taken into account because it increased slightly during an experiment -

3.3.4.7 Testing at National Research Council of Canada

Confined and unconfined compression tests performed at N.R.C. are reported by Baker et al (1981), Parameswaran and Jones (1981), Parameswaran (1980), Parameswaran and Roy (1981), and Jones (1978). The same test apparatuses have been used by all of these authors. The apparatus description and procedure given below is taken from Baker, Jones, and Parameswaran (1981).

A. Unconfined Compression Tests (σ_3 = 0 MPa)

Unconfined compression tests were carried out on test specimens 50 and 75 mm in diameter having length/diameter ratios greater than 2. Strain rates were varied between 10^{-7} and 10^{-2} sec^{-1}. Some tests were performed with the specimens exposed to the ambient temperature in a cold room maintained at -6°C. For these specimens sublimation was prevented by a cellophane wrapper. The test set-up is shown in Figure 3-8. An extensometer consisting of three displacement transducers located on the specimens 120° apart around the circumference, measured the axial deformation and tilting of the specimen. All tests were carried out on floor model screw-driven universal testing machines (Model 1116, Instron).

Figure 3-9 shows the low temperature bath arrangement for unconfined compression tests at temperatures between -2 and -15°C. Specimens were immersed in kerosene during the tests to control the temperature to ±0.1°C and to prevent sublimation of ice. No membrane was used to isolate the specimen from the kerosene. The bath temperature was maintained with an immersed heat exchange coil through which methanol was circulated from a Tenny low temperature bath.

B. Confined Compression Tests

Low Confining Pressures (σ_3 = 0 to 0.35 MPa)

A specially designed double-walled triaxial cell was constructed to carry out tests under low confining pressures. A volume measurement device developed by Mitchell and Burn (1971) was modified to measure automatically the volume displacement of the triaxial cell fluid at low temperatures. This allowed measurement of the total volumetric deformation of the test specimen under load. The axial deformation was measured using a displacement transducer mounted between the piston and the cell.

ation unit and cabinet were installed in conjunction with the MTS, for the purpose of controlling the temperature during tests.

The MTS machine at CRREL has an overall stiffness of the loading system equal to 3.6×10^8 kg/m. The hydraulic actuator used in this investigation had a capacity of 1.135×10^3 kg. Constant stroke rates from 1.27×10^{-5} cm/min to 2.54×10^3 cm/min are available on this machine. Figure 3-7 shows a schematic diagram of the MTS system, including the closed loop.

The deformation for the uniaxial tests was measured with LVDT transducers from end cap to end cap over the entire length of the dumbbell specimen. In order to determine the strain in the necked-down section of the specimen, an analysis was done based on the geometry of the specimen. The analysis shows that the deformation in the neck section is equal to $0.524\,\Delta L$ where ΔL is the total measured deformation. This analysis was checked by conducting tests on an epoxy resin model of a dumbbell specimen with a similar geometry, and a deformation of $0.546\Delta L$ was found. Using the analytical method gave a deformation of $0.548\,\Delta L$ for this same geometry. This close agreement verified the analytical solution of $0.524\,\Delta L$.

In the majority of tests conducted, a 25 metric-ton capacity load cell was used with an accuracy of $\pm 2\%$ of full scale. A 2.27×10^3 kg range of loading rates was used for all tests conducted.

During a test the three quantities recorded were load, axial displacement, and time. Several methods were used to record the measured signals of a test. For slow tests, load and displacement were recorded on a Hewlett-Packard two-pen model 2FRA X-Y plotter. Also during slow tests, load, displacement, and time were recorded on the strip chart Hewlett-Packard two-pen recorder, model 7100B. Load versus displacement was recorded on a Tektronix oscilloscope model R5103N, for the full range of loading rates. A transient recorder, Biomation model 802, which was not included in the basic console of the MTS, was used to measure load and time during medium speed and fast tests when the slewing rate of the X-Y plotter or strip chart was exceeded. A tape recorder was used for several tests to record load and displacement, but it proved to show no advantage over the transient recorder.

Compression samples were aligned for direct axial load with plastic jigs, and a ball seat was placed between the actuator and the end cap to minimize any bending stress.

minute. However, the maximum ram speed at which the operator could satisfactorily control the cell pressure was 2 in/min or a strain rate of approximately 6% per minute. The cell pressure was held to ±0.05 kip/sq.in. in the low pressure test (σ_3 15 kip/sq.in.) but varied by as much as ±0.20 kip/sq.in. in the higher pressure tests. The load was sensed inside the triaxial cell by means of an unbonded wire strain gauge displacement transducer coupled to the base (Figure 3-6). The axial displacements were measured by a linear motion potentiometer. An array of three dial gauges was mounted on the loading piston to check on the axial displacements.

The outputs of the load cell, the load and compensator piston LMP's and the pressure cells were fed to a recording oscillograph. The loads and confining pressures were recorded to accuracies of ±0.5 kip/sq.in. (axial stress σ_1 ±0.01 kip/sq.in.) and ±0.05 kip/sq.in. respectively. The load piston displacement was recorded to ±0.001 in. (axial strain ε_1 ±0.03%) and the compensator piston displacement to ±0.002 in.

Residual strains in the apparatus were evaluated using a steel standard under loading conditions similar to those employed for the test samples. The test data were adjusted accordingly. The volumetric strains $\Delta V/V_0$ resulting from deviatoric loading were calculated from the adjusted load and compensator piston data and are accurate to ±0.1%. The sample volumes (V_0) resulting from application of the confining presures were not measured because of difficulties related to the relative stiffnesses of the confining fluid and the test samples.

The initial step in the triaxial test was to apply the confining pressure. This was applied slowly until the required confining pressure was reached. In most cases, the pressure fell as the result of consolidation and compression. Subsequently, the pressure was adjusted until no pressure drop was observed. This process required a maximum of ten minutes.

D. Haynes et al (1975) report on uniaxial compression tests on frozen silt conducted on a relatively stiff servo-controlled testing machine at -10°C. Laboratory made samples were used. Inserts were placed in the moulds to produce dumbbell shaped test specimens. The test apparatus and a brief description of test procedures are described below, (after Haynes, 1975):

The frozen soil samples were tested on the MTS closed-loop electrohydraulic testing machine, model 907.52. A Bemco refriger-

examinations of the test samples showed that no leakage occurred. The clamping rings served a dual purpose as they provided guidance for aligning the test samples in the triaxial cell.

The triaxial apparatus (Figure 3.5) was designed for confining pressures in the range 0.5-50 kip/sq.in. Basically, it consisted of a compression cell, a manually operated volume-change compensator, a fluid pressure supply, and a means of measuring and recording the load on the sample, the confining pressure (σ_3), the piston displacements and the temperature. Stainless steel was used for all high pressure components.

The cell had an o.d. of 6.5 in. and i.d. of 2.0 in. Kerosene was used as the pressurizing fluid. The cell pressure was applied to 20 kip/sq.in. by an air-operated pump and to 40 kip/sq.in. by a hand pump. The pressure was maintained nearly constant by means of a hand-operated volume compensator.

The volume compensator assembly consisted of a piston-cylinder device, a crank-operated ball screw jack and a disc brake. The disc brake was adjusted so that it just resisted the thrust of the compensator piston on the jack. The operator, then, controlled the confining pressure by turning the compensator crank. The translation of the compensator piston was measured by means of a linear motion potentiometer and a dial gauge. The cell pressure was displayed on a Bourdon tube pressure gauge and sensed electrically by means of a string gauge pressure cell.

The mechanically operated volume compensator provided for direct control of the confining pressure by an operator. An automatic air-operated system was also considered, but was rejected because of problems related to sticking of the compensator piston. A more sophisticated servo-controlled system was not considered because of funding limitations.

The tests were conducted in a cold room maintained at $-10^{o}C$ $\pm 1^{o}C$. The temperature of the pressurizing fluid adjacent to the test sample was measured with a high pressure thermocouple to an accuracy of $\pm 0.01^{o}C$. Ambient temperature variations were damped by the fluid so that no significant temperature changes were observed during a single test.

The axial load was applied by a 150-ton universal testing machine. High strain rates were desired in order to avoid creep effects and better to approximate the strain rates resulting from shock loading. However, the choice of strain rate was limited by the range of the testing machine and the capability of the compensator device. The maximum ram speed available was 10 in/min which is equivalent to a strain rate of approximately 300% per

was performed at each of the following temperatures: 26.6°F (-3°C), 20.3°F (-6.5°C), 14°F (-10°C), and -22°F (-30°C). And each series included tests with the loading heat set to move at constant speeds ranging from 0.01 to 10 inches per minute.

Immediately before testing, each specimen was removed from a constant temperature tempering box, the membrane was peeled back from the ends, and the plastic end caps were removed. The specimen was then placed on a 6 inch diameter by 3 inch base platen and the load cell loading cap was placed on top of the specimen.

After centering the specimen under the load cell, a constant load of from 10 to 100 lbs. (depending on the loading range) was applied while the oscilloscope initial point display was positioned. At this time both the load cell and LMP input voltages were read and adjusted as necessary. The loading head was then raised a sufficient height to allow it to attain the predetermined constant speed before loading the specimen. A time photograph exposure of the oscilloscope screen was taken during the test until specimen failure.

B. Sayles (1973) also reports on triaxial tests on frozen Ottawa sand. Cylindrical samples 70 mm in diameter and about 152.5 mm in length were used to ensure a large ratio between diameter and soil particle size and to use an available test apparatus. All specimens were trimmed to insure that the ends were perpendicular to the axis and enclosed in two and sometimes three rubber membranes to prevent the intrusion of the confining fluid (ethylene glycol and water).

C. Chamberlain et al (1972) and Chamberlain (1973) report on high pressure triaxial tests on frozen earth materials. The triaxial test chamber was specially designed at CRREL. A complete description of the apparatus and brief procedures are given below (after Chamberlain et al, 1972).

Tests were conducted on right cylindrical samples 1.4 in. in diameter and 35 in. high encased in 0.025 in. thick rubber membranes (Figure 3-4). The membranes were sealed to the end caps by means of O-rings and a special clamping arrangement. This method of sealing proved to be effective, as post-test

In order to check test speeds (strain rates) a timing signal from a sine function generator was also driven by the LMP output.

Measuring devices included:

Load cell, 50,000 lb. cap., BLH type C
Load cell, 20,000 lb. cap., BLH type U-1
Linear Motion Potentiometer, 5" stroke, 5,000 ohms, Computer Instruments Corporation Type 111
Oscilloscope, Tektronics 502A
Function Generator, Hewlett-Packard LF, Model 202A
Potentiometer, Electro Scientific Industries Portomatic PVB 300
Universal Testing Machine, Tinius-Olson 300,000 lbs.
Camera, Polaroid Type Model C12

Before meaningful results could be obtained from the scope photos, compliance of the apparatus had to be taken into account. This was accomplished by making compliance test runs on the same hardware including the measuring systems used in testing. The oscilloscope pictures produced from the runs were averaged and an equation for the compliance of the apparatus was derived.

(ii) Procedure

The Ottawa sand specimen ends were squared using a special case-hardened vee-shaped miter box and various gradation of wood rasps and steel files. The ice specimens were squared using a machine lathe.

After measuring the volume and dimensions, the ends of the Ottawa sands specimens were capped with a thin layer of ice to avoid local stress concentrations caused by the relatively large sand grains in contact with the loading caps. The capping was accomplished by pouring a layer of $32^{o}F$ water on a flat glass plate, then setting the specimen on its plate and allowing the water to freeze in the cold room. The glass plate was removed by gentle warming. It was not necessary to cap the ice since the machine ends were smooth and perpendicular to the specimen axis. All specimens were sealed in circumferential rubber membranes and plastic end caps for storage until testing.

Before testing, all specimens were held within $\pm.1^{o}C$ of the test temperature for a minimum of 24 hours. This tempering time was checked using thermocouples embedded at the midpoint and quarter points of the axis of a control specimen. This check showed that 24 hours was sufficient time for the specimens to reach equilibrium.

At each temperature a series of the unconfined compression tests were conducted at different loading head speeds. One test series

7) After the peak load was observed on the recorder the driving mechanism was stopped and the confining pressure, if any, was removed.

8) The temperature of the cold bath was recorded and the triaxial cell was removed from the cold bath.

Most of the constant strain rate triaxial tests were conducted on the Wyeham-Farrance load frame. However, 15 tests were conducted using the Soiltest apparatus. In these tests the procedure was as noted above with the exception of step six in which the trace of the displacement curve was observed and adjustments of the strain rate were made as the test progressed.

3.3.4.6 Testing at CRREL

Sayles and Epanchin (1966) report on a test program to evaluate the influence of rate of loading on the unconfined compressive strength of frozen saturated Ottawa sand and polycrystalline ice. The equipment used in the test program and the test procedure is given below.

A. After Sayles and Epanchin (1966)

(i) Apparatus:

A constant speed gear driven universal test machine was used to load the specimens. The loads and deformations were measured using load transducers (20,000 and 50,000 BLH load cells) and a carbon strip, infinite resolution, resistance type linear motion potentiometer (LMP). The read-out from the load cell and LMP were displayed on an oscilloscope screen and photographed for record.

Both the 20,000 and 50,000 lb. load cells were driven by 6 volts DC recommended by BLH and as supplied by a 7.5V battery through a variable resistor. The LMP input was 50 volts, supplied by 8 7.5V batteries and 2-1.35 volt mercury batteries. This produced an output of 10 volts per inch of extension.

The load cell output was displayed vertically and the LMP output displayed horizontally on the oscilloscope. Vertical scales ranged from .5 to 2.0 mv/cm while horizontal settings were from .1 to .2 v/cm.

(ii) Procedure:

To reduce end effects, friction reducers made of a sandwich of two layers of polyethylene and a greased aluminum disk were placed on each end of the sample. Next the sample was placed on top of the pedestal and capped with a lucite cap. A protective membrane was placed over the sample and fastened with rubber bands. The sample was then transferred to another cold box where it was mounted on the triaxial cell base plate. Three additional light membranes and one heavy membrane were placed over the sample. The triaxial cell's cover was placed over the sample and bolted to the base plate. The loading ram was brought into contact with the sample and the entire cell assembly was transferred to a work bench and the confining pressure gauge was attached. Finally, the cell and appurtenances were transferred to the cold bath and the cell was filled with coolant. Before testing, the triaxial cell and sample were allowed to stabilize in the cold bath for 12 hours at -12.0°C. This complicated mounting procedure was necessary to insure that the sample was never exposed to an environment that had any contact with the ethylene glycol coolant used in the cold bath since this could cause disintegration of the ice.

Triaxial tests with constant strain rates were conducted on both confined and unconfined sand-ice samples. After the sample and triaxial cell had been in the cold bath for about 12 hours, the test procedure outlined below was followed:

1) The temperature of the cold bath was observed and recorded.

2) The force transducer and the displacement transformer were connected to the Sanborn recorder which was allowed to warm up. After an adequate warm up period both transducers were brought to a zero reading.

3) The load frame ram was lowered until it was just in contact with the triaxial cell's ram, with no load applied.

4) If the test was to be confined, the appropriate level of pressure was applied to the triaxial cell. If the test was unconfined, this step was omitted.

5) The drive mechanism was set at the desired speed (usually 0.006 in/min) and the loading ram was activated.

6) The trace of the load and deflection readings were observed on the recorder output charts. As the trace approached the top of the graph, the stylus was turned back using the zero suppression capability of the recorder.

temperature control. Temperature at the cold bath was monitored using a thermometer with scale divisions of $0.1^{o}C$ from which the temperature could be estimated to $\pm 0.012^{o}C$. The coolant used in the refrigerating unit was a mixture of about 1/2 ethylene glycol and 1/2 water. Figure 3-3 shows a schematic layout of the testing equipment.

Various types of transducers were used to measure the axial force and displacements during a test. The transducer used to measure the loads during the constant axial strain rate tests was a Strainsert Model Q-1096 stud transducer with a 15,000 pound capacity. Loads measured with this transducer were accurate to ±10 pounds. This unit had no provision for pressure equalization, and when the confining pressure was applied the transducer would indiate a negative load. The value of the negative load was set equal to zero and increases in load were measured from this value.

For the constant strain rate tests (samples 77-89) and the creep tests a Strainsert flat load cell type FL5U-2SP with 5,000 psi capacity was used. This load cell had an accuracy of ±5 pounds.

To measure the axial displacement, a Sanborn Linearsyn differential transformer was used. The transformer was attached to the triaxial cell with the core element bearing on a collar plate fixed to the cell's loading ram. This allowed measurement of axial displacement within the cell and eliminated all other displacement measurements. The accuracy of measurements was ±0.0004 inches.

The force transducer and the differential transformer were connected to a Sanborn 150 4-channel recorder for permanent display of the results.

Two different load frames were used for the test series. The constant strain rate tests (samples 77-89) and the creep tests were performed on a Soiltest load frame Model T-118-X with a Graham variable speed transmission. The transmission was of the screw type and allowed displacement rates to be changed while tests were in progress. All other constant strain rate tests were conducted on a Wykeham-Farrance variable speed loading frame. This frame had a 30 speed gear box with speed selections from 0.225 to 0.000024 inches per minute. The machine performed satisfactorily, but there was no provision for changing the rate of displacement once the machine had started. The results indicate that as the load was applied, the displacement rate dropped off from the selected rate and did not return to this rate until after the peak load had been reached.

Although most of the samples deformed very uniformly there were a few that indicated membrane leakage or eccentric loading. Flaring at one end of the sample was assumed to be caused by slight leakage of the coolant between the membrane and the lucite disk. Bending was caused by either a bad sample or by the sample slipping laterally on its supports and hence an eccentric load application. Note is made in the data when these defects occurred.

B) After B.D. Alkire (1972)

(i) Apparatus:

Since the triaxial tests covering a range of confining pressures from 0 psi to 1000 psi was conducted, the triaxial cell had to be constructed of a material that would withstand this range of pressures. The type of cell used was a special high pressure triaxial cell. The cell was a stainless steel Wykeham-Farrance triaxial cell constructed for a maximum working pressure of 1500 psi and tested to 2250 psi. The cell had a stainless steel hardened ram and adequate valves to provide for drainage and pressure control. Two base plates for the cell were specially designed and constructed at Michigan State University to provide for a 15,000 pound or a 5,000 pound capacity stud transducer. For the constant strain rate tests the base plate with the 15,000 pound capacity transducer was used. The creep and step-stress tests were performed using the base plate with the 5,000 pound capacity transducer.

In order to conduct the triaxial tests at pressures up to 1000 psi a pressure transmitting system utilizing pressurized nitrogen gas as the activating source was used. The gas was transmitted from the nitrogen tanks through a regulating valve to a high pressure cell. In this cell the gas was brought into contact with the coolant liquid which transmitted the pressure to the triaxial cell. The high pressure cell also kept the coolant from backing up the line into the nitrogen tank during depressurizing. Gauges were placed at various locations to monitor the pressure. A master gauge attached to the triaxial cell was used to read the confining pressure in the triaxial cell. This gauge had a 5 psi increment with an accuracy of 1/2 percent. The constant pressure regulator and the system described held the pressure constant during the tests with very little variation.

The other part of the system consisted of the refrigerator unit and its appurtenances which controlled the test temperature of the coolant. A micro-regulated portable refrigerating unit was used to control the temperature of the coolant. The coolant was circulated from the refrigerating unit to a cold bath in which the triaxial cell was immersed. This system provided very good

It is recommended that in future studies the lucite disks be replaced by disks of some material not subject to this type of deformation.

(ii) Procedure:

The same triaxial cell and testing machine were used for all tests. For constant axial strain-rate tests the load was applied directly to the loading ram by a variable speed mechanical loading system. Two deformation rates (0.0003 and 0.0006 inches per minute) were used. These rates were chosen because of ease in checking with the calibration of the Sanborn recorder. Note that the use of a constant deformation rate produces a slightly increasing true axial strain-rate due to sample shortening as a test proceeds.

The deformation rates were easily maintained except when the load was changing rapidly. Results showed that the maximum variation was less than 10 percent when observed over a 10 minute period, for all but the first few tests.

At the end of each test the immediate elastic recovery was measured. The remainder of the sample deformation was considered to be plastic and non-recoverable. No attempt was made to measure viscoelastic recovery since this was masked by the viscoelastic recovery of the lucite disks. No method was devised to separate the recovery of the disks from that of the sample.

The total observed deflection consisted of two parts, that contributed by the system and that contributed by the sample. The equipment deflection will be called system error and is composed of seating error and system elastic error as described earlier. The deflections contributed by sample deformation include elastic and plastic strains.

The variation in the density of the ice (0.900 to 0.913 grams per cubic centimeter for ice samples and 0.848 to 0.917 grams per cubic centimeter for sand-ice samples) caused some variation in the test results. These differences in ice density were assumed to be due to small air inclusions in the ice. For most samples there were no voids present that were large enough to be visible. If no inherent weakening of the ice results form these air inclusions, the effective area of the ice may be considered to be diminished by an amount proportional to the air contained. Test results were improved by correcting the computed stress on the samples by a factor proportional to the variation of the sample ice density to a standard density of 0.900 grams per cubic centimeter.

volume measurements were closed. Also, when volume measurements were made the thermistor opening was closed and when temperature measurements were made no attempt was made to measure volume change. When temperature was not recorded by the thermistor a laboratory type thermometer with scale divisions to $0.1^{o}C$ was used to measure the temperature of the coolant bath. The temperature could be estimated to $0.01^{o}C$. It was observed that the temperature inside the triaxial cell adjacent to the sample did not vary by more than $0.05^{o}C$ from that measured with the thermometer in the coolant bath. Temperature fluctuations in the triaxial cell were reduced as compared to changes in the larger coolant bath because of the delayed response time.

The elastic deflection of the loading system was evaluated by substituting a steel plug corresponding to the sample size, applying a load, and observing deformations with the differential transformer. This elastic deflection was close to 0.0008 inches per 100 pounds of load.

The first friction reducers were made by coating both sides of a piece of aluminium foil with a mixture of silicone grease and powdered graphite. A thin polyethylene film was then applied to both sides of the aluminum foil and the excess grease mixture was squeezed out with a hydraulic press. This sheet was then cut into disks of the appropriate size.

It was observed that the volume of grease and graphite which remained was sufficient to introduce unpredictable errors in deformation measurements. Grease expelled from the friction reducers during a test caused apparent sample deformation on the test record. This error was measured by means of the same steel plug used to measure elastic error and it was observed that the original friction reducers deformed up to 0.012 inches.

A modified friction reducer used only silicone grease spread on both sides of the aluminum foil placed in as thin a layer as could be applied by hand. The polyethylene films were then applied to each side of the aluminum foil and any entrapped air was worked out by hand. The modified friction reducers reduced the deformation error to approximately 0.003 inches and appeared to work as efficiently as the original ones.

There was also a seating error introduced by the sample coming into more perfrect contact with the lucite disks.

Tests with the steel plug revealed that there was some visco-elastic behaviour in the system presumably resulting from deformation of the lucite disks. For this reason no attemmpt was made to evaluate the time dependent recovery of the materials tested.

the triaxial cell is also a solution of ethylene glycol and water.

Alnouri (1969) performed constant axial strain-rate tests on the frozen Sault Ste. Marie clay and the sand-ice samples. Since the ultimate strengths of the frozen soil samples were expected to exceed the force transducer's loading capacity, a 5000 pound proving ring was used to measure the axial load. The load was applied directly to the loading ram by a variable speed mechanical loading system. A deformation rate of 0.00678 inches per minute was used. The deformation rate was maintained during the test, and periodically adjusted to give an approximate constant strain rate of 3×10^{03} inch per inch per minute. Results showed that the variation was less than 10% when observed over two minute periods. The constant axial strain-rate tests were conducted with three different constant confining pressures of 30 psi, 60 psi, and 90 psi. The confining pressure was applied prior to the axial loading in each case.

Details of Alnouri's test apparatus are given in the next section of this report.

A) After R.R. Goughnour (1967)

(i) Apparatus:

The entire triaxial cell (Figure 3-2) was immersed in a coolant, ethylene glycol and water mixture, maintained at a constant temperature by circulating through a microregulator controlled cold box. Temperatures were recorded using a thermistor (Yellow Springs Incorporated #901) held adjacent to the sample by a stiff wire. The thermistor was calibrated with the aid of a copper-constant thermocouple and a reference ice water bath. The temperatures recorded during the tests varied by no more than $\pm 0.05^{o}C$. The burette was calibrated directly to 0.01 cubic centimeters.

For tests run with confining pressure the triaxial cell was connected to a constant pressure source. To minimize leakage from the triaxial cell the openings used for temperature and

deformation increases continuously with compression and the stress-deformation curve does not have a peak.

3.3.4.5 Testing of Frozen Soil - Uniaxial and Triaxial Testing at Michigan State U.

A number of uniaxial and triaxial test programs have been performed at Michigan State University. Detailed equipment descriptions and test procedures from Goughnour (1967), and Alkire (1972) are reproduced herein.

Bragg and Andersland (1981) performed constant strain rate uniaxial compression tests using a similar triaxial apparatus to that used by Goughnour (1967). Sample volume change, based on fluid expelled from the cell was measured using a burette system. Cuylindrical samples 35.7 mm diameter with an L:D ratio of 2 were tested using a Wykeham-Farrance (Model WF-10050) variable speed test machine. Applied strain rates ranged from $8.3 \times 10^{-5} sec^{-1}$ to $8.1 \times 10^{-7} sec^{-1}$. No detailed test procedure is given.

Alkire and Morrison (1982) (Michigan Technological University) performed a study to compare soil response to freeze-thaw and repeated loading. Their equipment is shown in Figure 3-1.

> Cell pressures were generated by compressed air acting through a backpressure panel. The panel independently regulates both confining fluid and pore pressure. The air-driven loading ram is connected to an electro pneumatic regulator and opens to house air through a controlling valve which is used to increase or decrease the load. For the case of repeated loading, the pneumatic regulator is controlled by a function generator. Pore pressure was monitored with a pressure transducer mounted on the backpressure panel and the bottom drainage line to the freeze-thaw triaxial cell. Both transducers gave identical results. Samples subject to freeze-thaw cycling were frozen in a modified triaxial cell; see Figure 3-1. The cell has 9.52 mm copper tubing coil mounted around its inside perimeter. A cooling fluid (ethylene glycol) is circulated through the coil via a refrigerated circulating bath. The confining fluid used inside

7. In uniaxial compression tests, special attention should be paid to ensuring that the top and bottom surfaces of the specimen are parallel, that they are clearly formed and that they are centred on the plates of the testing machine. The specimen is positioned on a ring of the same diameter as the specimen inscribed in the centre of the lower plate. The top and bottom surfaces of the specimen are carefully cleaned with fine emery paper.

8. The specimens must be protected from the effects of exposure during long-term tests. This is accomplished by placing the specimen to be tested in an elastic rubber sheath, the diameter of which is larger than that of the specimen itself. The sheath is held in place by rubber bands mounted on the upper and lower plates of the instrument.

(ii) Procedures:

1. Rapid load action tests are carried out to determine the substantially instantaneous value of the limiting strength (temporary resistance) $\sigma_0 \sim \sigma_{us_0}$ and to determine the relationship between stresses and deformations which characterize the stress-deformation state at the initial moment of time.

2. In order to obtain all the indicated characteristics, the instrument to be used for the tests is fitted with an automatic rercorder and attachments which permit both axial and radial deformations of the specimen to be measured (data units, dial gauges).

3. The tests consist of subjecting frozen soil specimens to a continuously increasing load. The load is applied evenly and gently, but is increased rapidly so that the whole procedure is completed in approximately 30 seconds. The test ends with the failure of the specimen or the achievement of an axial deformation value equal to 20% of the initial height of the sample.

During the test the automatic recorder traces the compression pattern in coordinates of load P (Kg) - absolute deformation λ (mm), and the radial deformation gauge indicates the increease in the diameter of the specimen.

4. The nature of the stress-deformation patterns obtained in uniaxial compression tests of frozen soils depends on the type and temperature of the soil.

For brittle frozen soil the stress curve has a peak; for plastic frozen soils and frozen soils subject to viscous deformation,

3.3.4.4 Recommended Standard Test Procedures for Uniaxial Compression Testing

A. Uniaxial Compression - After Vyalov (1965)

(i) Apparatus:

1. Various types of hydraulic and electromechanical presses, as well as instruments used to test unfrozen soils (level presses, compression stands,etc.), may be used for uniaxial compression tests.

2. In selecting instruments for uniaxial compression tests of frozen soils, allowance should be made for specimen deformation by an amount not less than 20% of its initial height; maintenance of a given load for prolonged periods when conducting creep tests (within 5%).

3. Short-term tests are usually conducted with hydraulic and electromechanical presses.

4. Instruments for testing frozen soils at uniaxial compression are fitted with devices for measuring the axial and radial deformation of the specimen. Measuring devices intended for single and continuous measurements may be used to record deformations. Automatic deformation recording is necessary in certain cases during rapid testing.

The measuring devices must meet the following requirements: The measuring range in terms of the axial deformation of a specimen should not be less than 20% of its original height; the deformation measurement should be accurate to within 0.01mm. They should be capable of measuring the radial deformation of a specimen. For determining maximum radial deformation values, the Poisson ratio for frozen soils may be taken as 0.35.

5. For the measurement of axial deformations, clock-type indicators, rheostat and resistance data units and other devices may be used. Selection of the method of measuring will depend on the availability of equipment and the purpose of the tests. It is advisable to use special data units for measuring radial deformations.

6. Specimens used for uniaxial compression tests are cylindrical in shape with an h/d ratio of 2, where h is the height of the specimen, and d is the diameter, which must not be less than 4 cm. When testing coarse-grained soils and soils with ice intercalations, the diameter of the specimen should be 12-15cm.

A. Compression/tension Strength Ratios

It has been shown that the compression strength of a specimen is largely determined by the tensions generated in it as the result of compression. The high compression/tension strength ratios observed for rocks are indicative of the inefficiency of direct compression in developing tensile stress regions capable of producing unstable crack growth. Increased inhomogeneity of the specimen improves the efficiency.

It should be noted, however, that in some respects the inefficiency is not as severe as suggested. Thus, whilst direct tension does produce fracture at much lower stress (and energy) levels than compression, only one major fracture surface is produced. In a homogeneous material, compression failure produces a myriad of new surfaces. If the aim is to comminute the material to a given size, the tensile specimen will need to be re-broken many times, each time with at least the same energy expenditure, before the desired size is reached. The net energy used will still be appreciably less than for comminution by direction compression but the advantage of tension will not be as startling as sometimes quoted.

B. Effective Tensions

It is important to note that the localized tensions (σ_T)(see Fig.3.3.22a) which produce axial splitting in compressive fields must be compensated by localized compressions (σ_c) such that, over a section such as AA' the total force normal to the major applied compression is in equilibrium with that imposed on the boundary (equal to zero for a uniaxial test). The oscillation from tension to compression occurs on the scale of the inhomogeneity (grain to grain). The absence of a large scale tensile region due to the overall uniformity of the compression applied a the boundary, accounts for the essentially non-propagating character of the axial cracks. Any non-uniformity of the applied stress σ_x will superimpose larger scale tensile regions.* In the limit, as the uniform σ_z tends to a concentrated axial load acting at points AA' of the end planes then the localized tensions become superimposed on an essentially Brazilian test distribution (Fig.3.3.22) with tension over the major portion of AA. A propagating cleavage along AA' is consequently more probable. Any slight tangential tension produced by the use of end friction reducers, and stress waves produced by use of soft testing systems will also contribute appreciably to axial cleavage fracturing.

*This will result in longer axial cracks. In compression testing, for example, as the peak load is reached and the central portion of the specimen starts to dialte whereas the ends are restrained and relatively intact. This will give rise to marked non-uniformity of the applied compression. In turn this gives rise to the larger scale tensile regions, and accounts for the frequently observed slabbing or axial splitting type collapse.

$$\delta_S = \frac{E_S A_S}{L_S}$$

where: E_S is the loading modulus (axial stress-axial strain ratio on loading)
A_S is the specimen cross-section normal to the loading axis
L_S is the specimen length

(Note that this applies also to hydraulic jacks. Thus the stiffness of a jack may be raised appreciably by increasing the cross-sectional area of the piston and reducing the fluid volume (i.e. length of fluid column) under pressure. To operate a hydraulic loading system at maximum stiffness, the ram should be kept as close as possible to the bottom of its stroke. Use of a system of much higher capacity than required for a test (this implies a large cross-sectional area piston) will also tend to maximize stiffness of the hydraulic system. Much of the compliance of a hydraulic system is usually associated with presssure hoses, these should be made as rigid as practically possible.

As energy, W, is fed into the system (machine plus specimen) an amount W_m will be stored in the machine by deflection (δ_m) of the platens, (Fig.3.3.20), and an amount, W_s, will be required to contract the specimen. If we assume that for the strain rates operative during the test, shortening of the specimen can be continued without acceleration (i.e. quasi-statically) if the falling force-deformation path ABC is followed, then the reduction in force will cause closure of the platens, following the machine unloading path ADE, releasing part of the stored energy, W_m. If for a virtual increase or shortening the force exerted by the platens is greater than the force which can be 'quasi-statically sustained' by the specimen, then the specimen shortening will be accelerated by the unbalanced force acting on the mass of the specimen and the machine. The energy excess represented by the shaded area ADB will be available for this spontaneous acceleration. This system is thus unstable, and the specimen will rapidly disintegrate. If, on the other hand, the machine is very stiff such that the unloading behaviour is as shown in Fig.3.3.21, then no acceleration will occur. The energy represented by the area ABD is now a deficiency which must be added to the system in order that the deformation may take place. This system is thus stable, and permits the determination of the complete quasi-static force-deformation (or stress-strain curve OABC) for the specimen. The energy requirements and the detailed deformation behaviour of the specimen can then be determined.

3.3.4.3 Test System Stiffness

Baker's 1978 study used a soft load frame and compliant platens that further reduced the system stiffness. He states that all specimens failed in a ductile manner.

Only very recently have stiff servo-controlled machines begun to be used to evaluate the short term deformation behaviour of ice and permafrost. Fairhurst (1970) gives the following description of the effect of system stiffness on brittle fracture.

> It is becoming increasingly recognized that systems designed primarily for the mechanical testing of ductile materials are less than satisfactory for use with materials which may behave in a more brittle fashion for deformations beyond that at the peak load. This can be appreciated by consideration of the energy storage characteristics of the specimen and the testing system. (i.e. the composite of test frame, force generator e.g. hydraulic jack, hoses, valves...). In Fig.3.3.20 the overall stiffness of the testing system exclusive of specimen is K_m. Thus an axial load, F, applied between the machine platens will produce a total deflection (i.e. change in platen spacing) of δ, where
>
> $$F = K_m \delta_m$$
>
> Similarly, the axial stiffness (K_s) of a specimen will be defined as the ratio of the axial force (F) applied to the specimen and the reesulting axial deformation (δ_s), or
>
> $$F = K_s \delta_s$$
>
> If we assume that the loading machine (comprising the frame and all associated load generating components) is elastic, then the stiffness, K_m, may be represented as a spring (stiffness K_m) connected to a rigid ($K = \infty$) frame. Energy (W_m) will be stored in the spring, i.e. in the loading system where
>
> $$W_m = \frac{K_m}{2} \delta_m^2$$
>
> If the specimen has a constant cross-section then the loading (i.e. essentially elastic region) stiffness is given by

3) Aluminum disk platen
4) Maraset compliant platen.
Each specimen was subjected to a constant strain rate of 0.7 x 10^{-3} min^{-1} using an Instron universal testing machine (model 1127).

The compressive strength of the frozen sand was found to be about 25 per cent higher using the Maraset platens than with the other platen configurations at high slenderness ratios (~2.0).

Law (1977) proposed a procedure for designing compliant platens to match the characteristics of the specimen being tested. His design equations are based on the elastic parameters of the materials involved. Frozen sand is a viscoelastic material and exhibits non-elastic features prior to yield. All the specimens tested in this study exhibited a ductile type of deformation. The secant modulus at yield, determined using a standard compression test with steel platens, can be used as the modulus of compression for the specimen (E_s). This value inserted into the design equations would provide a platen that could be used in testing specimens to the yield point and remove the dependence on slenderness ratio as shown by the results obtained from this study.

Compliant platens would reduce the effect of rough ends on specimens and simplify procedures for specimen preparation. Smaller slenderness ratios would eliminate the possibilitiy of buckling and tilting. This would generally reduce the expense of sampling and testing and may reduce some of the variability due to the test conditions.

Sinha and Frederking (1979) studied the effect of system stiffness on the strength of ice (discussed earlier in this section). In comparing a stiff (steel platen) to a soft (Flexane platen) system they found that the ice strength was similar but the failure mode was different. With the stiff platen system true brittle failure occurred, while with the soft platen system ductile type yield occurred. They concluded that:

(i) increasing relative system stiffness leads to higher stress rates and consequent ice strengths, and

(ii) experimental fixtures (compliant platens, cardboard layers and ball alignment sockets) reduce relative system stiffness and lead to lower measured ice strengths.

$$\frac{V_p}{E_p} = \frac{V_s}{E_s}$$

where V_p, V_s are Poisson's ratios for the platen and specimen respectively.

This does not eliminate end-restraint adequately, however, since V_s changes throughout the loading cycle, whereas V_p remains constant. As the specimen approaches the failure load V_s (inelastically) increases well beyond the theoretical elastic limit of 0.5. The ends are consequently restrained appreciably near the failure load, high lateral tensions are induced, and collapse by lateral splitting of the specimen frequently ensues.

Baker (1978) performed a study on the effect of end conditions on the uniaxial compressive strength of frozen sand. He notes the following:

Friction between the platen and specimen produces radial restraint, so there is a triaxial state of stress near the end planes. Insertion of a highly compliant sheet between platen and specimen will change the sign of radial end forces from compressive to tensile, but does not eliminate the triaxial stress state. Irregularities in the specimen and planes can create stress concentrations that could lead to premature failure of the specimen (IAHR,1975). Stress gradients can be produced by eccentric loading and by lack of parallelism between specimen end planes or between specimen ends and loading platens.

One solution to the aforementioned problems would be to accept some frictional restraint at the specimen ends and to prepare specimens with large slenderness ratios (height/diameter). If the specimen is long enough, the mid-section is relatively free from end effects. Platens either more compressible than the specimen or less compressible than the specimen affect the specimen over an axial distance from the end planes of about one specimen radius. A slenderness ratio greater than two usually eliminates the effects of end conditions on compressive strength.

A testing program, using specimens of frozen sand, was initiated to investigate the influences of various end conditions employed in the uniaxial compression testing of brittle materials. Four platen configurations were considered:

1) Aluminum end cap
2) Aluminum disk platen with a rubber insert

> test chamber is controlled by the pressure regulator (or intensifier) so that no differential pressure exists across the chamber wall. Volume in the small test chamber is monitored by an EMA. The EMA can be modified to give a sensitivity of 200 mv output for 1 ml volume change for this application. This system configuration requires specially designed sample end caps and uses two of the fluid ports in the lower triaxial test cell closure to monitor the small volume fluid changes.

3.3.4.2 Sample End Conditions

Recommended standards for uniaxial compressive testing were given previously from Vyalov (1965) for permafrost, the I.S.R.M. for rock, and the I.A.H.R. for ice. The three recommended standards are very similar and each recommends slenderness ratios of 2 to 3, no end cap lubricants, and that samples be machined to close tolerances and very carefully aligned in the sample stack.

A review of published procedures, however, given above, indicates that there is not any general agreement on standard procedures. Many researchers report using friction reducers and the specifications for sample end preparation show considerable variance, from sophisticated milling machines to mitre boards with saws and files.

Fairhurst (1970) notes the following:

> The standard procedure is to carefully prepare a cylindrical specimen of the material to be tested, usually with a height:diameter ratio not less than 2:1.
>
> Since the material is usually heterogeneous it is very difficult to generate absolutely uniform axial pressure across the specimen. This non-uniformity may induce excessive lateral tensions (discussed later in this section). The non-uniformity becomes more severe as the centre of the specimen expands laterally with respect to the ends, restrained by frictional resistance at the loading platen/specimen interface. This problem can be somewhat reduced by 'matching' end platens (of the same diameter as the specimen) with the specimen, i.e. there will be no end restraint if

A water-submersible displacement transducer of the inductance type is fixed inside the upper part of the inner chamber, the transducer lead passing through an O-ring seal in the top plate. The unguided core of the displacement transducer is connected to the piston. A small hole through the inner chamber near the top enables the upper part of the inner chamber to communicate with the space between the inner and outer chambers which also has a duct to a valve in the bottom plate.

By connecting one valve to a back pressure supply and the other to the triaxial cell, any displacement of water in either direction in the pore-water duct causes the piston and hence the transducer core to move. A zero volume change four-way valve can be used to reverse the flow when the piston approaches the end of the stroke, and therefore extend the range of the device.

(vii) Ennies Measuring Accumulator

An alternate system capable of very sensitive total volumetric strain measurements has been developed and is marketed commercially by Terra Tek Systems Inc., Salt Lake City, Utah, and is described below.

Two Confining Fluid Volume Change Measurement systems are available providing different degrees of measurement accuracy. The simplest of the two systems consists of an Ennies Measuring Accumulator (EMA) plumbed into the confining fluid system between the regulator (or intensifier) and the triaxial test cell. An LVDT monitors piston movement in the EMA and hence gives an indication of confining fluid volulme changes. This option includes an additional signal conditioning unit to excite and monitor output from the LVDT. Sensitivity of the system is 20 mv output per 1 ml volume change. Isolation and by-pass valves allow the confining fluid to be brought to pressure before the EMA is connected into the system. The large volume of confining fluid in the triaxial test cell limits the volume change that can be detected using this system. The second Confining Fluid Volume Change Measurement System reduces the volulme of confining fluid being monitored and hence makes the measurement more sensitive to volume changes due to actual sample volume changes. For this system, a small test chamber is used to contain just the sample and end caps (Figure 3-16). This test chamber has an inside diameter just 0.5 inches larger than the sample diameter. The upper sample end cap passes through a seal in the test chamber so that the small volume of confining fluid immediately surrounding the sample is isolated from the rest of trhe confining fluid in the triaxial test cell. Pressure both inside and outside the

Again, devices with this type of system apparently are not commercially available.

(iv) Servomechanism System

Servomechanisms have been used in the past for automatic recording of liquid column heights in manometers. A sensing element to detect the liquid column height is used such that at balance or null point, there is no output. When the liquid height changes, an "error" signal is produced and amplified to drive a servomotor. The servomotor then repositions the liquid height sensor so the null point is re-established. The angular rotation of the servomotor can be used to record the changes in liquid height. The same principle has been applied to volume change devices.

(v) Mercury Pot System

A simple and reliable method of measuring volume change automatically used the Bishop self-compensating mercury constant pressure unit. The extensin of the spring in this unit is directly proportional to the volume of fluid from the soil sample and can be measured by a dial gauge or automatically recorded with a displacement transducer.

The drainage from the triaxial cell is connected to a regular burette for calibration purposes, whereas the other extreme of the apparatus is connected to the back pressure system. Two acrylic pots are filled with mercury and water as in the regular Bishop device. The pots are suspended by springs, one of the pots having displacement transducer in addition. As water drains from the sample, mercury will flow from one pot to the other, but its level will be constant in both pots because of the deflections of the compensating springs. The displacement transducer attached to one of the springs will record the deflection of it. A calibration of the output is obtained with the burette. For a regular size Bishop mercury pot (6.4 cm inner diameter) and a spring with 216 N/m stiffness, a deflection of a 0.001 mm represents a volume change of 0.0016 cm^3. Some problems in the measurement can develop with vibration.

(vi) Rolling Diaphragm and Displacement Transducer System

The device consists of two vertical concentric acrylic chambers between horizontal top and bottom plates. The inner chamber is separated into an upper and lower part by a brass piston incorporating a rolling diaphragm. The weight of the piston applies a small pressure differential across the convolute of the diaphragm whereby the low friction rolling action is obtained. The lower part communicates through a duct to a valve in the bottom plate.

(i) Burette System

A burette system is a calibrated tube containing a meniscus formed by two immiscible fluids. One fluid is water. The other fluid is a light oil, such as paraffin, kerosene, or silicone when there is a back pressure, and air when there is no back pressure. Since the meniscus moves in response to fluid flow through the tube, volume changes occurring in the sample are read visually by noting the location of the meniscus on a graduated length scale mounted beside the burette.

According to Davis (14), the several disadvantages of using a burette system to measure volume change are:

1) Resolution and range have opposing effects on each other. Burette systems with a large range have inadequate resolution for measuring small changes in volume. Very sensitive, fine bore burette systems must be very long to provide a reasonable range, creating excessive head drops for full travel.

2) Contamination generates problems. Even with burette systems of large diameters, a small amount of wall contamination causes the meniscus to behave poorly, making accurate readings difficult.

3) Readings from the burette systems are made visually. The burette system is not suitable for automatic logging of volume change.

(ii) Measurement of Meniscus Level

Systems that provide a measureement of the meniscus level are an extension of the burette system that incorporates a means of generating electrical output from the movement of the burette meniscus which can be recorded. Four different methods have been developed. These are (1) differential pressure measurement, (2) capacitance measurement, (3) float measurement, and (4) electrolyte volume measurement. Devices based on these methods of measurement apparently are not commercially available.

(iii) Gravimetric System

As an alternative to the burette system, the gravimetric system is designed to weigh the fluid to be measured. This provides an accurate volume change determination that, with the use of force transducers, will generate electrical signals for automatic recording purposes. Two types of gravimetric systems were found in the literature: direct weighing device and beam balance device.

which measures two diametral strains at the sample mid-height. The device is described in detail in section 3.3.4.10 (Testing at Terra Tek).

Cole (1978) describes a radial displacement transducer which does not rely on physical contact with the specimen during testing, (Figure 3-15).

> The device operates on the eddy-current-loss principle. A coil in the transducer induces an eddy current in an aluminium target. The magnitude of the eddy current generated is a functin of the distance between the face of the transducer and the target. Since the impedance of the coil changes as the eddy current changes, the coil impedance is a function of the distance between the transducer and the target.

Radial strain devices as described above are generally satisfactory for short term deformation behaviour tests, especially of cold permafrost. For long term, (very low strain rate or constant stress) tests however, devices that contact the specimen may be affected by creep at the contact points. Also for tests on warm permafrost (near $0^{o}C$) the sample may not deform uniformly in which case point diametral strains may be very misleading in calculating total volumetric strain.

Devices which measure volumetric strain by the change in confining fluid volume are not subject to the above two restrictions but encounter other problems with sensitivity, range, leakage, etc. Alva-Hurtado and Selig (1981) present a review of laboratory devices for measuring soil volume change. Detailed descriptions of each apparatus is beyond the scope of this report. The various methods available are briefly summarized below. For more information the reader is referred to the original article by Alva-Hurtado and Selig.

3.3.4 Short Term Strength Testing of Frozen Soil

3.3.4.1 Measurement of Volumetric Strain

For analytical purposes it is usually assumed that frozen soils exhibit zero volume change. An assumption which is necessitated because technical difficulties have generally limited strain measurement in frozen soils to one dimension. With improved analytic techniques and increased interest in permafrost engineering, the need to obtain more complete strain information from test specimens has been recognized. In conventional stress-controlled or deformation-rate-controlled triaxial tests, either total volumetric strains or radial strains can be monitored in conjunction with axial strains in order to complete the average or overall strain deformation.

Equipment designed to measure total volumetric strain must meet, at least, the following three criteria, (O'Connor and Mitchell, 1979):

(i) it must be capable of operating at temperatures below $0^{o}C$

(ii) it must be capable of measuring very small volume or deformation changes, and

(iii) it must be capable of operating in conjunction with confining pressures and space limitations in a triaxial cell.

Two basic methods can be used to determine volumetric strain:

(i) direct measurement of axial strain plus two discrete diametral strains, then

$$\Delta = E_1 + E_2 + E_3$$

(ii) direct measurement of total volume change of the confining fluid in a triaxial cell.

For the discrete measurement of diametral strain several different apparatuses are avilable. Vyalov et al (1966) describe a radial deformation gauge that mounts directly on the specimen. Alternately Terra Tek Inc. have developed an in-vessel cantilever diametral strain gauge device

To protect the surface of the ice specimen from penetration of the hydraulic fluid and possible loss in strength, a rubber membrane was placed on each specimen tested. The membrane had a thickness of 0.01 cm and had a tight fit on each end of the gauge length of the specimen. Inspection of the specimen after fracture showed that no fluid had touched the ice over the gauge length.

After the diameter was measured, the eccentricity checked and the rubber membrane placed on the specimen, it was inserted into the test chamber. Electrical connections to the LVDT and the pressure transducer were made. The needle valve to the accumulator was opened. The cam plate on the piston pump was adjusted to give a desired time to failure value. Except for the recorder and the air compressor, the entire apparatus was kept in a cold-room where the temperature was maintained at $-7.0 \pm 1.0^{o}C$. A remote control on the pump motor was used to start a test. The test chamber was hydraulically pressurized until the specimen fractured, which was indicated on the recorder by a momentary drop in pressure followed by a rapid increase. The test specimen was removed immediately following a test so that the mode of fracture could be examined.

Direct tension tests were done on laboratory made dumbbell shaped specimens of frozen soil by Haynes et al (1975). The end caps were frozen directly to the sample and tests were done on a relatively stiff servo-controlled machine. The method of applying the direct tensile force is given below.

Tensile forces were transferred to the tension samples through cables attached from the end caps to the actuator. Each cable was 0.56 cm in diameter and approximately 11 cm in length. The cables were designed to minimize twisting under the load, thus resulting in a true desired axial tensile stress. Hawkes and Mellor (1972) used a very similar approach and in their experiment found the tensile stress induced by cable twist to be only about 1% of the axial tensile stress.

For the series 2 tests the apparatus was modified so that ratios greater than 0.53 could be obtained. The design modification was proposed by Dennis Farrell and Donald Nevel of CRREL. The higher ratios were obtained in the series 2 test chamber (Fig.3.3.18b) by applying back pressure on the end caps which reduced the axial tensile stress. As before, the extended cups were attached to the ice specimen by freezing in place.

A schematic of the entire apparatus is shown in Fig.3.3.19. A three-phase, 2 hp a-c General Electric motor was used to drive a Vickers aircraft-type piston pump with a variable delivery rate up to 7.85 gal/min. A 1/2 gallon Parker Hannifin piston type accumulator assembled in the pressure line served as a bleed-off to achieve variable load rates and also minimized pressure surging and pressure pulsations.

A No.500 Soil Moisture air compressor with a 42.2 kg/cm^2 rated capacity returned the piston to a position of zero oil volume in the accumulator after a test. Ice specimen deformation was measured with a Schaevitz 300 SS-L linear variable differential transformer/transducer with a range of ± 0.762 cm. The hydraulic pressure in the test chamber was recorded with a Baldwin-Lima-Hamilton pressure transducer rated at 35.2 kg/cm^2 capacity and calibrated to $\pm 0.1\%$ of full scale. All fracture and deformation results were recorded on a Hewlett-Packard-Mosley two channel strip chart recorder.

The LVDT is assembled on the end of the chamber. The LVDT core was spring loaded in a unit assembly with the barrel so that it automatically returned to a zero setting after each test. The pressure transducer was attached to the test chamber at a 1.27 cm pipe port.

The LVDT measured the axial deformation over the entire specimen length. In order to obtain the deformation in the neck of the specimen, the simplifying assumption was made that the deformation in a section of the specimen was proportional to its cross-sectional area. Deformation in the neck was found to be 0.293 of the total deformation. Hawkes and Mellor (1972) used a value of 0.3 after calculations gave a value of 0.3 and a value of 0.29 was found by experiment. A value a 0.3 was used for data reduction in this study.

(ii) Procedure

After each specimen was removed from the mold its diameter was measured with vernier calipers to ± 0.00254 cm. Following this the eccentricity of each specimen was determined.

consists of split aluminum end cups with load-applying pin insert and a keeper ring. The conical section bears on its mating cup holder surface and transmits the uniaxial load without freezing the specimen in. Alignment of the testing machine should be checked, and a universal joint should be inserted to ensure concentric load application. This system has certain flexibility to re-adjust the specimen after preloading to check opposing strain output. In most cases, however, the specimen slides into proper position guided by the beveled bearing surface.

Probably the most desirable arrangement is to have right circular cylinders of ice frozen directly to end cups of the same diameter, but bond strength is a problem. Mellor (personal communication) has proposed the use of Synthane (bonded Bakelite) end cups on which the bonding surface is scarified to form a rough "hairy" surface. The Synthane end cup is spun in a lathe at a very low speed while a sharp facing tool traverses radially with a penetration of approximately 0.5 mm and a traverse speed giving a 0.5 mm spacing between the spiral grooves. Qualitative bond tests seem promising, and further development of the method is proceeding at the U.S. Army Cold Regions Research and Engineering Laboratory.

B. After Haynes (1973)

Haynes (1973) performed tests to evaluate the effect of compressive stress on the tensile strength of polycrystalline ice specifically to help interpret tests with combined stress states and in particular the Brazil test. The apparatus and test procedure used are given below.

(i) Apparatus:

The apparatus used in this study was proposed by Dr.Ivor Hawkes and designed by Donald Garfield and Dr.Hawkes at CRREL. It is similar to the device used by Baratta and Driscoll. The test chamber used in the series 1 tests, with compression tension ratios of 0.21 and 0.53, is shown in Fig.3.3.18a. The cups were attached to an ice specimen by freezing them in place when the specimen was made in the Lucite mold. A 0.008 cm difference in diameter between the cup and the cup holder permitted fluid flow out of both ends of the test chamber during the test. This oil flow minimized the sliding friction between the cup and the cup holder.

Although uniaxial testing procedures are straightforward for ductile materials, for brittle materials any slight stress concentration can cause premature failure and give erroneous results. Therefore, special care must be taken when designing a method for preparing ice specimens and testing them in tension at relatively high loading rates. To reduce end effect errors as much as possible dumbbell-shaped ice specimens can be used.

(ii) Preparation of a Dumbbell Ice Specimen

In preparation for machining dumbbell specimens the cores should be cut into right circular samples by using either a cut-off wheel or facing off with a lathe. A special alignment jig or tray to hold the sample is necessary to ensure plane and parallel ends. These cylindrical specimens should be cut at least three core diameters long to provide a test section length of approximately one core-diameter. The test section diameter should be one-half of the core diameter. The transition region between the test section and enlarged ends must avoid stress concentrations due to short radius fillets. For this reason a transition radius is chosen almost equal to core diameter, large enough to minimize possible stress concentrations. After machining, the dumbbell specimens should be cold soaked at the test temperature for 3-4 hours prior to testing.

(iii) Tensile Pulling System

Most past tensile testing procedures have favored freezing the dumbbell ice specimen into metal end caps. Probably, the best designed freezing technique is presented by Hawkes and Mellor (1970). Dumbbell tensile specimens are tacked to aluminum end caps by freezing a few drops of water between the specimen and the base of the cup. Alignment is ensured by use of a special assembly jig and is checked after the tacking procedure is completed.

All acceptable specimens are finally bonded firmly to their end cups by pouring freezing water into an annular space between the cup wall and specimen. Tensile specimens fastened in their end cups are connected to the testing machine by two short lengths of stranded steel cable (see Fig.3.3.17). Checks during evaluation trials of the pulling assembly determined the effects of cable twisting and eccentric loading to be slight. Finally, uniformity of applied stress was verified by strain gauging a dumbbell epoxy model. However, the bond may be unsatisfactory when specimen temperature is very low, since there is differential thermal strain between ice and aluminum.

Another method has been employed which does not freeze the dumbbell ice specimen to the end holders. The tensile pulling system

relative system stiffness and stress rate, i.e., increasing the relative system stiffness increases the stress rate.

Laboratory measurements of ice strength have been evaluated in terms of either nominal strain rate, or strain rate at yield or peak strain rate in cases where an extensometer has been fixed to the specimen. The results are usually plotted in terms of stress-strain curves. This type of presentation does not adequately take into account the influence of relative system stiffness. The influence of relative system stiffness is also not taken into account by relating strength to the peak strain rate. On the other hand, stress-time behaviour, related to the essentially constant stress rate that is found to be associated with constant rate of cross-head movement tests, quite definitely reflects relative system stiffness.

Since the relative system stiffness affects the stress rate, the strength measured in a so-called "constant strain rate" test will be a function of the test system used. Most strength testing on ice has been done on relatively low load capacity machines and with necessarily large specimens. Also test arrangements have often included ball alignment sockets and layers of compliant material to improve end conditions. These, taken together with all the attendance interfaces, indicate that most testing of ice has been at low relative system stiffness and hence strength results in the literature would tend to be on the low side. Now, however, larger and stiffer machines are being used and it would be reasonable to expect higher ice strengths. In addition, closed-loop test machines, which have the possibility of performing true constant strain rate or stress rate tests, are beginning to be applied to testing of ice and they should provide new insights on ice behaviour.

3.3.3.4 Uniaxial Tensile Testing of Ice

A. After the I.A.H.R. Working Group on Ice Problems "Standardization of Testing Methods for Ice Properties - 1980."

(i) Introduction

Uniaxial tensile strength can only be determined unambiguously through direct tension testing. Any substitute indirect test method, such as ring tensile, brazil, or flexural tests induce complicated stress states within the sample and stress-strain relationships have to be assumed in calculating the test results.

(ii) Instron model 1127, 0.25 MN capacity, Permafrost Cold Room, Division of Building Research, National Research Council of Canada, Ottawa.

(iii) MTS model 907.52, 1.25 MN capacity, U.S.Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.

Strain-time records from two tests run at a cross-head rate of 0.2 cm/min (nominal strain rate $1.3 \times 10^{-4} s^{-1}$) on two different test machines both indicate that the final strain rate approaches (within experimental error) the nominal rate, but the strain paths were very different. The 1.25 MN capacity test machine, which has a stiffer load frame, approaches a constant strain rate condition more quickly than the 0.1 MN capacity machine. Also the strain and time to failure are smaller with the larger capacity machine. Stress-time results show that the loading condition can be fairly accurately described as constant stress rate. In both cases the nominal strain rate was $1.3 \times 10^{-4} s^{-1}$ but the larger capacity and stiffer machine attains a substantially higher stress rate. Failure stress is similar in both cases, however, a significant difference in failure behaviour is evident. With the higher capacity and stiffer test machine, the failure can be characterized as brittle. The less stiff machine (lower head capacity) results in a more ductile-like yield failure.

In the second test series two approaches were employed to achieve lower relative system stiffnesses: (i) introducing a compliant platen and (ii) using specimens of reduced length. The stress-time results of two tests with different platen materials but identical 50 x 100 x 250 mm specimens performed on the 0.1 MN capacity machine at a cross-head rate of 0.1 cm/min show that at higher relative system stiffness (steel platen) the stress rate is higher than for the lower relative system stiffness (Flexane platen). The ice strength is similar in both cases but the failure modes are different, a premature brittle type of failure occurring for higher relative system stiffness.

As part of the test program samples of varying length were also tested with each of the platen materials at the same strain rate.

The authors conclude that for a given nominal strain rate increasing the machine load capacity, which increases the relative system stiffness, results in an increase in stress rate. Reducing the specimen length or introducing compliant platens, which reduces relative system stiffness, correspondingly reduces the stress rate. From this it can be seen that there is a relation between

Following testing the sample is photographed. A small hole is drilled at mid-height and the sample temperature is taken. The sample is then slabbed, one half being retained for crystallographic studies and the second half used for salinity determination.

D. Testing at N.R.C. (After Sinha and Frederking, 1979)

In the case of ice normal operating temperatures are within 10 to 20 degrees of the melting point so this material is in a high temperature state and exhibits non-linear viscoelastic behaviour with a strong dependence on time and temperature. As normal grain diameter for ice is in the millimetre range, large specimens are required which in turn means the load application capacity of test machines is often fully utilized. The effect of machine stiffness has, however, been little recognized.

To investigate this a series of experiments were conducted by the National Research Council with specimens of identical ice type on test systems of various stiffness.

Two series of experiments were carried out to investigate test system stiffness on ice behaviour. In both cases columnar grained ice of 5 mm average grain size was used. Specimen preparation was identical and test temperature in all cases was $-10^{o}C$.

The first series comprised identical specimens on three different test machines. The specimens were 50 x 100 x 250 mm long prisms. The long axes of the columnar grains were normal to the 100 x 250 mm face. Load was transmitted to the ice through 16 mm thick steel platens at either end of the specimen. A 19 mm diameter steel ball placed between two conical seats facilitated alignment and uniform load application on the specimen ends. Strains were measured with an extensometer of 150 mm gauge length mounted directly on the specimen. Continuous records of load and strain versus time were made. The three following test machines were used:

(i) Instron model TTDM-L, 0.1 MN capacity, Snow and Ice Cold Room, Division of Building Research, National Research Council of Canada, Ottawa.

the temperature never rose above the pressure melting point, and the second was that the temperature had to be allowed to equilibrate after applying the pressure.

C. Uniaxial and Triaxial Testing at GEOTECH, Calgary, Alberta

At the time of writing a test program is being conducted by GEOTECH on a multi-year ice core from near Banks Island, N.W.T., for Gulf Canada Resources. The test system and the system capabilities are described on the following page. The test frame is located in a walk-in freezer where temperature can be controlled from 0 to -40°C. Sample preparation is done using a band saw and the lathe in the cold room. Samples are machined to a diameter of about 95 mm and a length of about 250 mm. Sample ends are machined perpendicular to the sample axis and parallel within a tolerance of 0.0254 mm.

The test system is a stiff servo-controlled system capable of either constant strain rate or constant stress testing. Constant strain rates from 10^{-7} to 10^{-2} sec^{-1}. Loading conditions are set using a wavetek function generator to program the servo-controller.

Load and deformation measurements are all made in-vessel using a load cell and cantilever axial and radial deformation gauges, similar to those described above for testing done by Terra Tek Inc. A separate LVDT also monitors cross-head movement. Data acquisition is done with an H.P. model 4035-BX-Y-Y plotter and a TEAC model R-61 F.M.Recorder.

Uniaxial tests are done under ambient cold room conditions. For triaxial tests, the sample is wrapped with a polyethylene jacket. Confining fluid is maintained at the same temperature as the cold room. Thermocouples are used to monitor confining fluid temperature during each test. No lubricants are used on the platens.

(i) Mechanical Testing Procedure

The mechanical testing apparatus used is shown in Figure 3-14. The ice sample, S, was placed in a cell capable of withstanding at least 100 MNm^{-2} hydrostatic pressure. The pressurizing fluid was Dow Corning Silicone fluid 200, hand-pumped through the line, H. A piston, P, sealed by two O-rings applied a uniaxial compressive force to the sample. The whole sat inside a cold box on the base of a model 1116 Instron mechanical tester. All the tests reported here were done at $-12\pm1^{o}C$, the temperature usually varying less than $0.1^{o}C$ during a test, as monitored by a thermocouple (T, Figure 3-14) inside the cell. The Instron load cell, being outside the high pressure cell, measured not only the uniaxial load applied by the crosshead, but also the force of the hydrostatic pressure on the piston, P, and any frictional force of the piston itself. The friction was small and was taken into account by doing dummy runs without a sample. The hydrostatic presssure was more difficult to take into account because it increased slightly during an experiment - as the piston descended, the volume of the cell was decreased and the hydrostatic pressure was, thus, increased. Typcially, the hydrostatic pressure rose by 1 MNm^{-2} during an experiment. The output of the Instron load cell, therefore, was a linearly increasing load due to the increasing hydrostatic pressure plus the load-time curve of the ice sample itself.

The linear, hydrostatic, part of the curve was extrapolated and subtracted from the curve to give the load-time curve of the ice sample alone. The hydrostatic pressure was also monitored independently with a Heise gauge, and this confirmed the linear increase in pressure.

The Instron compressed the ice at a constant speed of deformation. The time axis of the Instron strip chart recorder was, therefore, taken to be directly proportional to the amount of compression, $\Delta\ell = \ell_o - \ell$. The true strain, $\Delta\ell/\ell$, (not ℓ_o) was then calculated.

For most tests the samples were immersed directly in the silicone fluid, without covering them first with a thin rubber sleeve. Some were protected from the oil by such a sleeve but these showed no difference in yield or fracture stress from the unprotected samples. Further tests were done at one atmosphere pressure, using an air bath rather than the silicone fluid, both with and without rubber sleeves, and these tests also showed no significant effect of either the oil or the rubber sleeves.

The application of the hydrostatic pressure raised the temperature of the oil and hence the ice by several degrees. Therefore, two precautions were necessary. The first was to make sure that

zero time at the start of the press. The zero time of the experiment had to be adjusted during data reduction because no seating load had been applied to the specimen. The true time zero was determined by extrapolating the load time plot to a zero load and using this as zero time. This method was preferred to that using the zero time established when the press was started since the gears require a certain time to become engaged and begin loading the specimen. The time zero value for the LVDT was selected as the above value.

The deformation of the sample was checked at regular time intervals to ensure that it was being loaded at a constant rate of displacement. The output of the LVDT, the load cell, the thermistor, and the time clock were recorded at regular time intervals during the experiment on a remote data acquisition system located outside the cold room. The data were recorded using a Techtran cassette recorder. The data were reduced using a Fortran computer program and the results plotted using a Calcomp bed plotter.

The test was continued until the stress versus time plot stabilized at a constant stress and until the sample had undergone a strain of greater than 15%.

Upon termination of testing each sample was removed from the test cell. The final dimensions were taken and the shape sketched. The sample was weighed to determine if any weight loss had occurred during the experiment. Thin sections of the sample were then prepared to determine the affect of the deformation of the sample on the initial ice crystal structure.

B. Triaxial Testing - Inland Waters Directorate, Department of the Environment, Ottawa

Triaxial tests were performed to study the effect of confining pressure on the compressive behaviour of ice over a wide range of strain rates from the nominal creep range to the brittle fracture range (10^{-6} to x 5 x 10^{-3}sec^{-1}). Laboratory made samples within L:D ratio of 3 were used. The apparatus and test procedure are briefly described below (after Jones, 1978).

to further reduce the friction, and the sample was placed on the platen using the centering hole as a guide. The upper platen was lowered on the sample using the same procedure as above. The cell was then assembled around the sample and filled with paraffin oil using a tank under low pressure to force the oil into the cell. The sample was ready for testing in the constant displacement rate test frame.

The constant displacement rate experiments were conducted in a cold room maintained at $-3\pm5^{o}C$. The experiments were all conducted at test temperatures warmer than the room temperature. This required that the fluid circulating through the cooling coils be heated above the ambient room temperature. The experiments were performed with these temperature conditions to ensure that the sample would cool down if a constant temperature bath failed. This temperature condition also ensured that heat flowed radially outward from the cell to the cold room. The radial heat flow away from the cell helped to reduce temperature fluctuations of the sample.

The cell containing the sample and the confining fluid was transferred from the preparation cold room maintained at $-5^{o}C$ to the sample testing cold room at $-3^{o}C$. The cell was placed inside the insulated cabinet, on the cooling plate which separated the test frame from the cell. The fluid lines from the constant temperature bath were attached to the cell. The fluid temperature in the bath was checked to ensure that it was at the desired test temperature. The variable resistor dial on the constant temperature bath was locked at this dial setting. The temperature measuring probe was placed into the cell and attached to the date recorder. The cell temperature was recorded and the pump on the constant temperature bath activated. The ethylene glycol mixture circulated through the cooling coil within the cell and the cooling plate beneath the cell.

While the cooling fluid was being circulated, the LVDT and the load cell were adjusted to their zero position for the experiment. This was accomplished using an electronic monitor within the cold room. The insulated cabinet surrounding the cell was closed. The cell and the sample were allowed a minimum of twenty-four hours to establish an equilbrium temperature. During this period the temperature of the cell was recorded and it was noted that the sample reached a stable temperature in about 10 hours.

The displacement rate used during each experiment was selected using the nominal rates applicable for each set of gears on the testing machine. The press was then started and all the measuring devices were recorded to establish their zero readings and

accurately to .0013 mm. The load cells were capable of measuring a load of 18 kN. The thermistors were calibrated using a quartz thermometer to +0.001°C; therefore, the thermistor measured a temperature 0.01±.005°C.

(ii) Procedure:

The ends of the sample were machined at right angles to the vertical axis of the sample. Generally two passes of the shell mill were required to prepare one end of the sample. A final cut of about 0.02 mm was made. The shell mill was then passed over the sample a minimum of two times to ensure that no cutter marks were protruding from the sample. These cutter marks would be stress concentration points during the loading of the sample. The sample was removed from the rotary table and turned end-for-end and remounted in the rotary table. The sample was checked to ensure that it was securely mounted and then machined to the required length for testing. The final steps in preparing the sample were the same as above. The sample was now weighed and the dimensions recorded.

In order to ensure reproducibility in all measurements from sample to sample, a guide was established for the measurements of each sample. The dimensions of each sample were established by taking three measurements of the sample length and three measurements of the sample diameter. The diameter was measured at the top, middle and bottom whereas the length was taken at three independent locations on the sample. The sample was weighed allowing the bulk density to be calculated. With the dimensions established, the sample was ready to have the centering holes drilled and to be mounted in the cell.

A centering hole was drilled in the top and bottom of each constant displacement rate sample to facilitate centering of the sample during setup. This was required because each end platen had a securely attached Teflon friction reducer which caused aligning problems during sample set up.

The sample was again mounted in the rotary table and secured. The shell mix was removed and replaced with a cutter head of 3 mm diameter. The center of the sample was located and a centering hole drilled to a depth of 6 mm. The sample was removed and turned end-for-end and remounted. The center again was located and the centering hole drilled. The sample was removed from the rotary table and was ready for mounting in the test cell.

The sample and the test cell platen were wiped clean to ensure that no grit was lodged between the sample and the Teflon-coated load platen. The lower load platen was coated with paraffin oil

A. Testing at the University of Alberta - After Sego (1980)

(i) Apparatus

The constant displacement rate tests were performed using an 18 kN capacity Wykeham Farrance constant displacement rate loading press. The displacement rate could be varied between 1.2 mm/minute and 0.00049 mm/minute. The maximum diameter of sample was limited to 70 mm because of spacing restriction between the bars of the reaction frame. This restriction limited the triaxial cell diameter which could be used in this test program.

The triaxial cells used required extensive modification to obtain temperature control, temperature measurement, reduction of friction on the platens, and centering of the sample on the platen.

The triaxial cell was selected since it allows for a cell fluid to surround the sample which reduces ablation of the sample. The cell fluid employed was a light paraffin oil. This fluid also acts as thermal mass surrounding the sample which helps maintain a constant temperature in the sample during the experiment.

The temperature of the sample was maintained constant by circulating a mixture of ethylene glycol and water through the cooling coils, which act as heat exchangers, mounted within the triaxial cell. The temperature of the ethylene glycol mixture was maintained constant during the experiment by circulating the fluid through a Hot Pak constant temperature apparatus. This apparatus was capable of maintaining the temperature of the circulating fluid constant for prolonged periods of time.

The temperature of the triaxial cell fluid was measured using a temperature measuring probe located at the mid-height of the sample between the sample and the copper cooling coil. The temperature measuring probe was constructed using a stainless steel tube and an Atkin #3 thermistor bead. The details of its construction and calibration are given by Roggensack (1977).

The base of the triaxial cell was isolated from the load frame by a cooling plate mounted between the cell and the frame. The cooling fluid from the Hot Pak apparatus was circulated through this plate. The triaxial cell and measuring equipment were islolated from the temperature fluctuation of the cold room by being housed in an insulated cabinet.

The measuring instruments used in these experiments were a linearly variable displacement transducer (LVDT), thermistor, and temperature compensated strain gauge load cell. The Hewlett Packard 24 DCDT LVDT was capable of measuring deformations

(width), correcting the result from reference curves to be established by a separate systematic investigation.

In the conventional uniaxial compression test, axial force is applied to the ends of a right circular cylinder through steel platens that make direct contact with the test specimen. Friction between platen and specimen produces radial restraint so that there is a triaxial slate of stress near the end planes; the triaxial field is significant over an axial distance from the end planes of about one specimen radius. Interposition of a highly compliant sheet (elastic or plastic) between platen and specimen often changes the sign of radial end forces, but does not eliminate the triaxial stress slate.

The usual procedure of testing ice in uniaxial compression in the conventional way is to use a specimen that is long enough to provide a mid-seciton that is reasonably free from end effect stress pertubation (length/diameter ratio of 2 to 3).

Extreme care is exercised in specimen preparation to produce end planes that are normal to the axis of symmetry and flat within very strict tolerances. A very thin sheet of compressible material (e.g. paper) may be interposed between specimen and platen to compensate for very small surface departures from parallelism. Flexure and bending of the specimen are avoided by strict alignment procedures and by provision of high rigidity in the loading device to avoid rotation or lateral translation of the platens.

3.3.3.3 Testing of Ice - Uniaxial and Triaxial

There is considerable interest in the short term deformation behaviour of ice, largely related to determination of ice loads on offshore structures in Arctic regions. Recommended standard procedures for uniaxial and triaxial ice testing were given earlier in this section. Equipment and procedures used in recent ice test programs at the University of Alberta, the Department of the Environment, Ottawa, and tti GEOTECHnical resources ltd., Calgary, are given below. Finally, the results of a test series conducted by the National Research Council of Canada, to evaluate the effect of test system stiffness on the strength of ice is discussed.

3.3.3.2 After I.A.H.R. Working Group on Ice Problems: 'Standardization of Testing Methods for Ice Properties 1980' Uniaxial Compression Testing

Since the mechanical properties of ice, especially the compressive strength, are highly temperature and strain rate dependent, laboratory tests should be performed under controlled temperature conditions and the testing machine should provide a strain rate control system in which an extensiometer attached to the specimen regulates the plate velocity in such a way that the strain rate is constant (closed loop testing machine). The laboratory testing machine should allow strength measurements over a range of strain rates from 10^{-5} to $10^{-1}sec^{-1}$. The applied load should be measured by a load cell of adequate capacity in order to provide sufficient resolution of the results.

After the ice has been collected from the field or grown under laboratory conditions, rough cutting of prismatic ice blocks or of cylindrical core is advisable in order to obtain manageable sample sizes. Three different shapes are in use: (i) cylinders, (ii) prisms, and (iii) cubes. Since there is general agreement that tests on cubes may introduce significant errors, it is suggested that the use of such specimens be discontinued in the conventional method of testing. In recognition of the fact that a large amount of data exists for cubic specimens, appropriate conversion formulae, similar to those developed in the field of rock mechanics and concrete technology, should be developed for ice.

Cylindrical specimens are usually prepared by a coring drill. Specimen diameter should be within a range of 7.0 to 10 cm. Specimen ends must be plane and parallel within close tolerances; this can be achieved by a rotary cut-off machine, by a milling machine, or by a lathe. The specimen length should be approximately 2.5 times the diameter.

Prismatic specimens for laboratory tests should be prepared by the use of a milling machine or surface grinder, while for field tests the cut-off machine and the lapping and melting method can be used, the latter one with caution.

The compressive strength, and probably also the tensile strength, of ice may depend on the ratio of sample size to crystal size. In order to be independent of this ratio, it is desireable to have the sample width, d, some 15 to 20 times the crystal diameter, d_c. Since the requirement would lead sometimes to very large specimens, it may be advisable to use a standard cylindrical or prismatic specimen of 7.5 cm to 10 cm diameter

2. The ends of the specimen shall be flat to 0.02 mm and shall not depart from perpendicularity to the axis of the specimen by more than 0.001 radian (about 3.5 min) or 0.05 mm in 50 mm.

3. The sides of the specimen shall be smooth and free of abrupt irregularities and straight to within 0.3 mm over the full length of the specimen.

4. The use of capping materials or end surface treatments other than machining is not permitted.

5. The diameter of the test specimen shall be measured to the nearest 0.1 mm by averaging two diameters measured at right angles to each other at about the upper-height, the mid-height and the lower height of the specimen. The average diameter shall be used for calculating the cross-sectional area. The height of the specimen shall be determined to the nearest 1.0 mm.

6. Moisture can have a significant effect on the deformability of the test specimen. When possible, in situ moisture conditions should be preserved until the time of the test. When the characteristic of the rock material under conditions varying from saturation to dry is required, proper note shall be made of moisture conditions so that correlation between deformability and moisture content can be made. Excess moisture can create a problem of adhesion of strain gauges which may require making a change in moisture content of the sample. The moisture condition shall be reported as described in "calculation of the water content of a rock sample." Method 1, ISRM Committee on Laboratory Tests, Document No.2, 1977.

7. Load on the specimen shall be applied continuously at a constant stress rate such that failure will occur within 5-10 minutes of loading, alternatively the stress rate shall be within the limits of 0.5-1.0 MPa/s.

8. Load and axial and circumferential strains or deformations shall be recorded at evenly spaced load intervals during the test, if not continually recorded. At least ten readings should be taken over the load range to define the axial and diametric stress-strain curves.

9. It is sometimes advisable for a few cycles of loading and unloading to be performed.

10. The number of specimens instrumented and tested under a specified set of conditions shall be governed by practical considerations but at least five are preferred.

is the diameter of the specimen. The thickness of the platens shall be at least 15 mm or D/3. Surfaces of the discs should be ground and their flatness should be better than 0.005 mm.

4. One of the two platens shall incorporate a spherical seat. The spherical seat should be placed on the upper end of the specimen. It should be lightly lubricated with mineral oil so that it locks after the dead weight of the cross-head has been picked up. The specimen, the platens and spherical seat shall be accurately centred with respect to one another and to the loading machine. The curvature centre of the seat surface should coincide with the centre of the top end of the specimen.

5. Electrical resistance strain gauges, linear variable differential transformers, compressometers, optical devices or other suitable measuring devices. Their design shall be such that the average of two circumferential and two axial strain measurements, equally spaced, can be determined for each increment of load. The devices should be robust and stable, with strain sensitivity of the order of 5×10^{-6}.

Both axial and circumferential strains shall be determined within an accuracy of 2% of the reading and a precision of 0.2 percent of full scale.

If electrical resistance strain gauges are used, the length of the gauges over which axial and circumferential strains are determined shall be at least ten grain diameters in magnitude and the gauges should not encroach with D/2 of the specimen ends, where D is the diameter of the specimen.

If dial micrometers of LVDT's are used for measuring axial deformation due to loading, these devices should be graduated to read in 0.002 mm units and accurate within 0.002 mm in any 0.02 mm range and within 0.005 mm in any 0.25 mm range. The dial micrometer or LVDT's should not encroach within D/2 of the specimen ends.

6. An apparatus for recording the loads and deformations, preferably an X-Y recorder capable of direct plotting of load-deformation curves.

(ii) Procedures:

1. Test specimens shall be right circular cylinders having a height to diameter ratio of 2.5-3.0 and a diameter preferably of not less than NX core size, approximately 54 mm. The diameter of the specimen should be related to the size of the largest grain in the rock by the ratio of at least 10:1.

variety of test apparatuses are reported in the literature. Only recently have factors such as overall system stiffness, load platen configuration, etc., begun to be investigated. Hence, there is no apparent agreement within the research community on apparatus standards for short term behaviour tests.

Triaxial test procedures are generally the same as for uniaxial tests. In triaxial testing the sample is generally raised hydrostatically to the desired confining load, after which the deviator load is raised rapidly to failure. Uniaxial tests are often performed in a triaxial cell with zero confining load in order to maintain test temperature control. Unconfined and triaxial testing are therefore discussed together in the following sections.

3.3.3 Short Term Strength Tests For Rock and Ice

3.3.3.1 Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials (After the I.S.R.M.)

(i) Apparatus:

1. A suitable machine shall be used for applying and measuring axial load to the specimen. It shall be of sufficient capacity and capable of applying load at a rate conforming to the requirements set in Section F (Procedures). It shall be verified at suitable time intervals and shall comply with accepted national requirements such as prescribed in either ASTM Methods E4: Verification of Testing Machines or British Standard 1610, Grade A or Deutsche Normen DIN 51 220, DIN 51 223, Klasse 1 and DIN 51 300.

2. A spherical seat, if any, of the testing machine, if not complying with specification 4 below shall be removed or placed in a locked position, the two loading faces of the machine being parallel to each other.

3. Steel platens in the form of discs having a Rockwell hardness of not less than HRC 58 shall be placed at the specimen ends. The diameter of the platens shall be between D and D+2 mm where D

3.3.2 Short Term Deformation Behaviour

The short term deformation behaviour of permafrost material is used to evaluate 'instantaneous' elastic properties of the medium. For activities such as ground fragmentation (drilling, excavation, etc.), the short term response is of dominant concern.

Most experimental research has been directed toward the long term, (creep), deformation behaviour (discussed in the following section). Such behaviour is usually referred to as ductile or plastic. However when loads are applied very rapidly, as in impact situations and especially at low temperature, frozen material may react in a very brittle manner.

Short term behaviour is usually investigated using uniaxial and triaxial compression and tension tests. Considerably more research has been done on the short term behaviour of pure ice than on permafrost material. Since the ice component of permafrost is an extremely important factor governing the overall material behaviour recent ice test experimental apparatuses and procedures are included.

There are no standard procedures for short term behaviour tests in permafrost. Vyalov (1965) gives the most detailed procedure. Although now somewhat dated it is still generally followed by many investigators. Standard procedures for uniaxial compression testing of rock, as set out by the I.S.R.M., and recommended standard procedures for uniaxial compression and tension testing of ice, as set out by the working group on ice problems of the I.A.H.R., are included for comparison. All of the above recommended procedures for short term behaviour tests are very similar.

Because permafrost materials may exhibit a very wide range of strength, especially between warm permafrost, (near $0^{o}C$), and colder permafrost, ($<-5^{o}C$), testing equipment must accommodate a wide load range. A wide

3.3 STRENGTH AND DEFORMATION PROPERTIES

3.3.1 Introduction

In this section of the report, the test apparatuses and procedures used to evaluate the strength-deformation behaviour of permafrost materials are reviewed. In section 3.3(b) short term (brittle behaviour) testing is reviewed while in section 3.3(c) long term (creep behaviour) testing is reviewed. In each case test apparatus and procedure descriptions are given for a particular author. As much as possible various researchers from the same research group (e.g. CRREL,N.R.C.,etc.) are grouped together.

Although no standard test procedures yet exist for permafrost testing, published standard procedures from associated areas such as rock mechanics and ice mechanics are included for comparison.

The majority of research has been directed at long term creep behaviour with most researchers favoring the uniaxial creep test. Recently increased interest has also been shown in short term behaviour. Most testing has been done using man made rather than natural permafrost samples.

In very general terms test procedures are reasonably consistent but in detail this is not so. Details of sample machining, end preparation, jacketing, temperature curation, etc., vary widely while the use of friction reducers, compliant platens and the importance of system stiffness are controversial.

pots and the lower fixed pots. The constant pressure apparatus is shown in Fig.3.4.5.

The axial deformation was measured simultaneously with two different measuring devices, a Linear Differential Transformer (Sanborn Linearsyn Differential Transformer Model No.575 DT-500), and a dial gauge with 0.0001 inch divisions. The outputs of the linear differential transformer and the force transducer were fed into a 2-channel recorder (Sanborn Recorder Model 7702B with a Sanborn Carrier Pre-amplifier Model 8805A).

(ii) Procedure

A constant axial pressure was supplied by a loading frame supporting a dead weight of lead bricks. The loading frame was lowered onto the loading ram by a mechanical loading device at a relatively fast rate. It took less than 5 seconds for the total load to transfer to the sample through the ram. And since the dynamic effects are very small, they were assumed to be negligible. To compensate for the increase in cross-sectional area as the sample deformed, lead shots were added to the dead load. The axial stress measured at the bottom of the sample and the axial deflection measured at the top of the sample were both recorded continuously on the charts of the recorder, at the highest possible sensitivity of the recording system. By observing the axial deflection data it was possible to know when the creep process had passed the primary creep stage and entered the steady state creep stage. When that stage was reached, and with axial loading constant, an increment of confining pressure was applied on the sample for a period of thirty minutes. Then the confining pressure was increased by four more increments of the same value, each increment applied for the same duration. In some of the creep tests, the confining pressure was decreased at the end of the test by increments of the same value, and the axial creep deformation was observed. The creep test was conducted with temperature held contstant for at least 24 hours prior to testing, and all through the test period.

B. After O.B. Andersland and W. Akili (1967)

(i) Apparatus and Procedure

Axial loads up to the selected unit stress were applied to the specimen using an electrically powered mechanical jack to lower dead weights at a rate close to 1.0 in/min. Upon sample deformation, a constant unit stress was maintained by adding lead shot to dead weights to compensate for the small increase in sample

area. Preliminary measurements showed no volume change (±0.01 cu.cm.) during deformation, hence constant volume deformation was assumed. Part of the initial dead load consisted of preselected amounts of lead shot in buckets with funnel shaped bottoms and a 1 in. dia. clamped hose. Stress reduction was accomplished simply by removing the hose clamp and allowing the lead shot to drain from the buckets into containers in a matter of seconds. For smaller stress reductions, a small container with lead shot could easily be lifted from the dead weights. Confining pressures were limited to about a six inch head of coolant liquid on all samples. Time and axial deformations (±0.0001 inc. accuracy) were visually observed and recorded as needed for each test. On completion of each test and after removal from the cell the appearance of the sample was noted and the final water content taken.

C. After B.D. Alkire (1972)

(i) Apparatus and Procedures

The procedure for conducting a uniaxial creep test was basically the same as the triaxial tests. The preliminary steps were the same as steps 1-4 listed in Section 3.3b on triaxial constant strain rate tests. After the load was applied the trace of the deflection curve was observed and at predetermined intervals small increments of weight were added to the sample to compensate for the increase in cross-sectional area and to maintain a constant stress. The increments of weight were noted and used to check the load readings obtained from the recorder. The tests were allowed to run for approximately six hours before the load was removed. The samples were allowed to recover for one hour, then the triaxial cell was removed from the cold bath and disassembled.

(ii) Step Stress

In step-stress testing the deviator stress was held constant and the confining pressure applied to a sample was changed by increments or steps. Except for the loading stage, the step-stress tests were conducted in the same manner as the uniaxial creep tests. During loading the selected level of stress was applied to the sample which was permitted to deform in the uniaxial state of stress for 60 minutes. At the end of this time an initial increment of confining pressure of 100 psi was applied to the sample. After the confining pressure was applied it was necessary to add weight to the dead load to retain the selected level of deviator stress. This was accomplished by observing the load

trace on the recorder and adding weight until it returned to the initial value. Additional increments of confining pressure were added at 120, 180, 240, 300, and 360 minutes. The total confining pressure after each of these increments was 200, 400, 600, 800, and 1000 psi, respectively. When operating at elevated confining pressure, the membranes were easily ruptured causing several of the step-stress tests to be terminated.

3.4.2.5 Testing at CRREL

A. After A.R. Gardner et al (1982)

(i) Apparatus

The apparatus is used for strength and creep tests on 38 mm diameter by 76 mm high specimens of frozen soil at temperatures down to -20°C. Load capacity is 35 kN with a maximum confining pressure, limited by the ram seal, of 1.8 MPa.

Figure 3.4.6 shows a schematic of the testing apparatus and Fig.3.4.7 a block diagram of the main components. The specimen, surrounded by two neoprene membranes, is held between two platens in the cylindrical steel triaxial cell (internal dimensions 200 mm diameter by 270 mm high), which also acts as the reaction frame. Load is applied through the bottom platen by a ram, travelling through a low friction Rolofram seal, driven by an hydraulic piston. Confining pressure is applied by pressurising silicon fluid inside the cell. This fluid is cooled by circulating a methanol/water mixture from a refrigeration unit through a copper coil inside the cell. The whole apparatus is mounted on legs, with a total height of 1.5 m.

Load, deformation, temperature and confining pressure are monitored through transducers and an analogue-to-digital convertor by the microcomputer, which in turn controls specimen load through a digital-to-analogue convertor and motor driven regulator in the piston supply. In calculating specimen deformation, due account is taken of system stiffness, and system deformation is subtracted from the measured value.

The test data is displayed on the microcomputer screen, with up-dates of averaged values (from sets of ten) of each reading every second. Data is also recorded on a printer at selected time intervals and, if required, on an X-Y plotter. In the event of system malfunction a failsafe pressure shut-down device is incorporated.

B. After F.H. Sayles (1968)

(i) Apparatus

Three types of loading devices were used to accommodate the different strength and deformation characteristics of the frozen sands.

Tests to determine the instantaneous compressive strength and short-term creep strength of frozen soils with relatively high resistance were performed in a 20,000 lb. capacity air-actuated hydraulic press. Loads were applied to the test specimen by means of an unconfined test chamber placed in the press. The press is capable of head movement rates up to 18 in/min. For creep tests, vibration-free constant loads can be maintained by the hydraulic press for extended periods of time within 2% of the applied load for loads greater than 3000 lb.

Creep tests in which large deformation occurs were performed on a constant stress press (capacity 4000 lb.) (Fig.3.4.8). This press features a programming cam that maintains constant axial stress to within 1% of applied stress on the test specimen during deformation. The load-programming is based on the assumptions that the cross-sectional area of the specimen remains uniform throughout its length during deformation, and that the volume remains constant throughout the test.

Long-term creep tests resulting in small deformation were performed on a lever-type press (capacity 2000 lb.). As the sample deforms, the height of the fulcrum is adjusted to maintain the loading level approximately horizontal.

(ii) Test Chamber:

The unconfined compression chamber in the hydraulic press is basically a frame with a leveling base upon which the test specimen rests. The loading piston mounted in recirculating ball bushings provides a base plate for the load measuring transducer. This transducer is in direct contact with the top spherical surface of the test specimen end cap. This arrangement permits measurement of the load applied to the test specimen at any time. Average deformations are measured by two linear motion potentiometers mounted diametrically opposite each other on the circumference of the load transducer.

(iii) Load and Deformation Measurements

All loads applied to test specimens in the hydraulic and constant stress presses were measured with Baldwin-Lima-Hamilton load cells having appropriate load ranges.

Hydraulic pressloads were measured using the load cells with readout on one channel of a Leeds and Northrup Azar G-type X-Y recorder. After calibration, loads were measured continuously to within 1.0% of the applied load.

Average axial deformations of test specimens in the hydraulic press were measured using two carbon-strip, infinite resolution, resistance-type linear-motion potentiometers mounted diametrically opposite each other on the load cell and movements were recorded on one channel of the L and N recorder. Using calibration charts, deformations were measured to within 0.0025 in. for movements less than 0.25 in. and 0.005 in. for movements greater than 0.25 in.

Constant-stress-apparatus loads were measured with the load cell and read manually using a B-L-H type N portable strain indicator. Loads were determined accurately to within 0.3% of the applied load. Deformations were measured using dial indicators with 1/10,000 in. gradations and a sensitivity of 2/100,000 in.

Constant load lever-type-press loads were determined by computing the hanger weights using the lever arm ratio. The load applied to each specimen was checked by placing a load cell in the specimen test space and reading the load with the hanger weights in place. Deformations were measured using the same type of extensometer as was used in the constant stress apparatus.

(iv) Temperature Control

Test temperatures of 25^{o}F and lower in the walk-in cold room were controlled to within $\pm 1^{o}$F. To damp temperature fluctuations to less than ± 0.50 ^{o}F, tests were conducted in enclosures constructed of 2 in. thick rigid type insulation (Styrofoam).

Test temperatures above 25^{o}F were controlled by heating and circulating air within the insulated test enclosures. Each test specimen was housed in a split Lucite cylinder to reduce temperature fluctuations of the air surrounding it. Heat was supplied by light bulbs mounted in the fan air-stream. The temperature was regulated by a mercury-column-type thermo-regulator which activated a relay to supply heat upon demand.

Air temperatures within the Lucite enclosures surrounding the test specimen were held constant well within ±0.1°F of the desired temperature.

(v) Temperature Measurements:

Temperatures 25°F and lower were measured to the nearest 0.5°F with a mercury thermometer placed within the insulated enclosure. Inside the Lucite enclosure a thermistor sensed the temperature of the air surrounding the test specimen and the readings were recorded every 1.25 min. on a 12-point L and N Type H recorder, to the nearest 0.2°F. Test temperatures above 25°F were measured to within 0.1°F using the same sensing and recording system but with increased sensitivity. Thermistor readings were checked daily using a manually operated Wheatstone bridge. Cold-room temperatures (outside of enclosures) were recorded continuously.

(vi) Procedure (After Sayles, 1968, 1973, 1974)

At each test temperature a series of compressive type tests were conducted by first determining the instantaneous strength of the frozen soil and then performing creep tests at reduced stress levels. Each test series included constant stress or constant load compression tests performed at stress levels of approximately 60, 40, 20, 10 and 5% of the average instantaneous strength. One test series was conducted at each of the following test temperatures: 15°,25°,29° and 31°F (-9.45°,-3.89 -1.66°,and -0.56°C). Whether constant stress or constant load tests were performed depended upon the magnitude of the applied stress and the expected deformation. Constant load tests were used for high and low stress levels where small deformations were expected, while constant stress tests were performed at intermediate stress levels (i.e. in the range of 15 to 40% of instantaneous strength) where the deformations were expected to be large.

The compression creep test on each specimen was performed by first applying a sealing load of approximately 2 psi (1.38 x $10^4 N/m^2$) to the specimen to ensure positive contact between it and the components of the loading system, and then applying the test load in less than 2 seconds. Instantaneous strengths were determined by loading the silt specimens at an average applied strain rate of 0.14/min and the clay specimens at 0.15/min. After each test was completed, photographs were taken of the test specimens and water contents were determined.

3.4.2.6 Testing by Woodward-Clyde Consultants

A. After J.A. Shuster (1971)

(i) Apparatus

The apparatus is similar to the triaxial shear and uniaxial consolidation equipment used in a conventional soil mechanics laboratory. The main components of the apparatus are two massive steel loading frames, similar to conventional consolidation test frames, with integral load-controlled sample loading mechanisms, and a refrigeration system. Each frame consists of four test positions. Frame 1 is equipped with regulated high and low pressure gas diaphragm* loading mechanisms for uniaxial testing. Frame 2 is equipped with regulated high and low pressure gas for pressurizing triaxial cells. The axial load mechanisms on this frame are of the weight and lever type. The refrigeration system is independent of the two test frames. A more detailed discussion of the various components of the test frames follows.

The two test frames are served by a single refrigeration system. It consists of a 1,8000 Kcal/hr (at -30°C) primary freon refrigeration plant which cools a 190 liter agitated ethylene glycol and water bath (40% water) that supplies the circulation system. The bath contains more than 100 times the volume of the circulation system thus minimizing the effects of thermal disturbance in the system and providing a stable heat sink. The circulation system, exclusive of the motor and rotary pump, consists of eight branches connected in parallel. Each branch corresponds to one test position and includes a variable (0-300 watt) heat element

and needle valve to regulate the temperature of the position during testing. Temperatures throughout the system are monitored with copper-constantan (Type T) thermocouples connected through a gang switch to a digital thermometer. The premium grade thermocouples used have an absolute value resolution of about 0.5°C. However, temperature differences can be measured to within about 0.05°C.

Test frame 1 is designed to maintain a constant axial load on samples indefinitely by use of gas pressure. Bottled nitrogen gas or compressed air is precisely regulated and passed into a diaphragm unit which provides load regulation on the sample between 0 and 3,200 Kg. The load is transmitted from the diaphragm unit through load rods to the sample.

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* The diaphragm transmits the gas pressure acting on it to a piston of smaller area. The mechanical advantage is 26:1.

Test frame 2 is designed to maintain constant triaxial cell pressure and constant axial load on samples indefinitely. The cell pressure is maintained by precisely regulated bottled nitrogen, for pressures over 11 kg/cm^2 and compressed air for lower pressure. Axial load is maintained by a weight and lever system with a capacity of about 1350 kg. When higher capacities are required the triaxial cell can be used in one of the previously described diaphragm actuated loading positions on test frame 1. Figure 3.4.9 is a schematic illustration of the operating components of the four triaxial test positions on test frame 2, with the exception of the conventional weight and lever system.

The fluid used in the triaxial cells is a silicone oil. It was selected for its overall stability throughout the temperature and pressure ranges used during testing. The more important properties of this fluid are tabulated below.

Specific Gravity 25 ^oC	Viscosity Centistokes 25 ^oC	Coefficient of expansion cc/cc/ ^oC	Thermal Conductivity Cal/sec/cm/ ^oC	Specific Heat Cal/gm/ ^oC
0.960	100.0	0.00096	0.00037	0.340

The samples are thermally isolated from the aluminum base of the cell by a plastic disc. The combination of the cooling coil arrangement, lucite disc, and the type of cell fluid limits thermal gradients in the test samples and assists in damping any temperature oscillations which may occur in the coolant circulation system. Temperatures in the triaxial cell are recorded at the top and bottom of the sample, in the cell fluid and at the inlet to the cooling coils. Dial gauges accurate to 0.01 mm, are used to measure axial deformation of the samples in the triaxial cell. This corresponds to a resolution of about 0.007% of the sample height of a typical 15 cm high sample. Volumetric deformation of the sample is measured by changes in the volume of the cell chamber fluid. These changes are visible as vertical displacements of the fluid meniscus in a manometer connected with the cell fluid. The reservoir and manometer cross sectional areas were selected and calibrated to permit direct volume change readings to a resolution of 0.08% of the sample volume. Total volume changes of as much as 20% may be read on the manometer. Simultaneous vacuum de-airing of the cell fluid, cell, and manometer provide assurance that measured volume changes are free of compressible gas effects. All volumetric readings are corrected for temperature and pressure to STP (20^oC and 0.0 psi g).

(ii) Procedure

The 'static' test procedure is about the best method of characterizing the time and temperature dependent rheology of frozen soil now available. However, multiple identical samples of natural permafrost frequently are not obtainable. Also samples which are apparently similar may exhibit considerable heterogeneity when loaded, resulting in excessive data scattering. For these reasons it is usually necessary to test a series of 6 to 8, or even 10, specimens at a single temperature though theoretically not more than 3 to 4 should be required. The 'incremental' procedure is a theoretically less satisfactory procedure, but it provides all of the necessary data with a single test; therefore, data scatter is not a problem. However, two or more additional samples should be tested under a single constant stress until creep failure occurs to confirm the validity of the results; hence, the need for three to four samples in a series.

Prior to conducting either the static or incremental tests it is necessary to assemble the samples into the apparatus and allow the samples and cells to equilibrate under the selected test temperature. For most soils a period of 24 hours is normally sufficient to recompress the sample and stabilize the temperature regime in the apparatus. Temperature control is critical and is generally one of the most difficult factors to regulate during testing. For test temperatures near $0^{o}C$ variations must be held to less than $\pm 0.1^{o}C$. For temperatures below $-10^{o}C$, variations of as much as $\pm 1.0^{o}C$ are acceptable. The duration of the period to achieve temperature equilibrium is short, usually not more than 2 hours. In general, for sands, an acceptable criteria for equilibrium under a given stress is that axial compression in the last 10 hours should be less than 1% of the total axial compression observed to that time. For silts and clays this should be extended to less than 1% in the last 20 hours. After the samples and the apparatus have come to equilibrium, the specific tests can be conducted.

The 'static' test procedure is most conveniently run in three phases. The first phase consists of applying a rapidly increasing stress to a single sample until failure occurs. The stress should be applied smoothly and sufficiently rapidly to fail the sample in about half a minute. The stress deformation data is most conveniently obtained by electronic recording equipment; however, visual observation of dial gauges showing axial deformation and pressure during the application of the load will provide satisfactory data. The maximum deviator stress attained

in this manner is proportional to the instantaneous shear strength of the material (τ inst.).

The second phase of the 'static' test procedure then consists of applying three different stress levels to three separate samples. The stress levels ar arbitrarily selected as 20, 50 and 80% of the maximum deviator stress determined from the first phase of testing. The stress levels are applied and axial deformation vs. time is recorded for each sample until creep failure or equilibrium is reached. If periodic volume change measurements indicate that the sample is deforming radially under the applied load then the load should be adjusted accordingly to maintain the desired stress constant. The test should be a constant stress test. A constant load test may be satisfactory for many soils, but the problem of data scatter and interpretation may be complicated considerably if radial sample deformatin occurs during such a test. The data obtained from these tests should be plotted with axial deformation as the ordinate and time as the abscissa. The resultant curves should indicate two and possibly three distinct intervals of time to creep failure (T_f). Failure being defined as the point at which the slope of the deformation-time curve begins increasing and rupture or collapse deformation is imminent. For a single soil it is desirable to have values of T_f spanning four or more magnitudes of time intervals, i.e., 0.1, 1.0, 10.0, 100.0 and 1,000.0 hours. The three initially selected stress levels may satisfy several of these.

The third phase of the 'static' test procedure consists of applying three additional stress levels selected on the basis of the results of the phase two tests to induce failure at time intervals corresponding to those needed to span the desired range. Though this procedure sounds somewhat vague, in practice it is quite straight forward and rarely is it necessary to run a series of more than the two testing cycles of three samples each. As the equipment is designed to process 8 samples simultaneously, the entire three phase test sequence can be set up at one time. Those samples not initially under stress are held under equilibrium conditions until the desired stress level for testing is determined and the next phase of testing can be initiated.

The results of the three phases of 'static' testing generally provide three principle relationships. The first is between the applied stress and the duration of time until progressive creep occurs and failure is imminent. The second is between the applied stress and the deformation it induces after various periods of loading. The third relationship is between the increase of

deformation, under a given stress and the duration of the loading period.

The 'incremental' test procedure is also conducted in three phases. The first phase is identical to the first phase of the static test procedure. The second phase consists of applying incrementally increasing stress levels to a single sample. The applied stresses starting at about 10% to 15% of the maximum deviator stress determined in phase one and increasing by about 10% for each increment. The intent being to induce progressive creep failure after at least six increments of loading. Each stress level should be applied rapidly and smoothly and held for a period of at least 24 hours prior to increasing the the next load. If time permits, uniform period durations of 48 or 72 rather than 24 hours are desirable. At some point during this loading procedure the yield point of the soil will be exceeded. Any stress in excess of the yield, if left on long enough, will induce progressive creep failure. The purpose of the incremental test procedure is to define this limiting condition. Unfortunately it is not apparent while the test is in progress. The data from this phase should be plotted as shown in Fig.3.4.10 and 3.4.11. The angle point on the curve in Fig.3.4.11 is the yield point at which the internal soil-ice bonds in the sample yield and undamped creep will occur for any applied stress greater than that coinciding with this point. Heavy plastic or ice rich clays at temperature close to freezing may not exhibit a marked angle point. In such a case the 'static' test procedure previously described is necessary to define the time of failure vs. stress characteristics of the soil.

The third phase of the incremental test procedure consists of confirming the validity of the second phase results. There is a cumulative destruction of the sample during incremental creep loading which may not be the same as the destruction imposed by the classic step function of stress applied over a period of time until equilibrium is reached or creep failure occurs. In many cases the load history does not effect the results from a practical point of view. However, it is necessary to determine if strain or stress hardening during incremental loading has had a significant effect on the results. The third phase of testing consists of applying a single stress level to a sample that is about 10% to 20% greater than the stress which coincides with the yield point determined during phase two. This sample should be maintained under this stress until creep failure occurs. The results are then used to approximately determine the creep function $K(\Theta,T)$ for a 24 hour period of loading at the test temperature. This $K(\Theta,T)$ from the static test should coincide with the

deformation coefficient A (Θ,T) determined from the flatter slope of the plot for the incremental data, as shown in Fig.3.4.11, for the same period of loading and temperature. If these two values do not coincide reasonably well then the incremental test procedure results are not valid. In such a case, it is probable that the creep characteristics of the soil have been affected by the load history during testing and only the static test procedure is valid.

The strength and creep deformation procedures discussed above have been presented for a single series of tests to characterize the material at a single test temperature. If desired, additional 'static' or 'incremental' test series can be conducted at one, or preferably two, widely separated additional temperatures to completely characterize the time and temperature controlled rheology of the soil.

3.4.2.7 Testing by B.Ladanyi and J.Arteau (1978), G.Aas (1980), and E.C.McRoberts et al (1970)

None of the above give any detailed test procedures. All of the authors describe the tests as 'constant stress'. Ladanyi and Arteau and McRoberts et al both comment on the need for periodic load adjustments, either manually or automatically, to maintain a constant stress regime.

McRoberts et al note that their system allowed temperature control to $\pm 0.1^{o}C$, but that because of the long duration of the testing some difficulties in temperature fluctuation due to occasional power failures, etc. were encountered.

Aas tested samples with an L:D ratio less than 1.0 between aluminum end caps. He does not make any comment on the validity of the test results derived using these very short specimens.

3.4.3 Tests on Ice

3.4.3.1 Testing at the University of Alberta

A. After D.C.C.Sego (1980), Uniaxial Constant Stress

(i) Apparatus

The constant stress experiments wre conducted using a lever-assisted loading frame to apply a constant load. The lever for this dead load frame was copied from the Wykeham Farrance constant displacement rate direct shear apparatus. This gave a mechanical advantage of five times, thus reducing the amount of dead load required for each experiment. The dead load system of applying a constant load to a sample has been used by all previous authors working on the creep of ice. It was also used in this program because a constant load can be maintained indefinitely.

The cells used were designed to hold the sample and surround each sample with paraffin oil to reduce ablation. The cells contain a copper cooling coil through which a cooling fluid was circulated to maintain a constant temperature. The upper and lower platens were coated with Teflon to reduce the friction between the sample and the platen. The cells were not designed to maintain a confining pressure, thus no cell cover was constructed.

The system of transferring the load from the lever system to the upper platen was similar to the transfer system in the direct shear apparatus. The transfer mechanism was designed to fit around the outside of the insulated cabinet which housed the measuring equipment and constant stress cell. The LVDT holder also held the temperature measuring probe and was attached to the load ram. The sample displacement was thus measured from the ram and not the top of the sample. All the instruments were housed within the insulated cabinet to reduce temperature fluctuations.

Each load transfer system was aligned to ensure that the load ram and the lever housing were acting on a plumb line in order that no lateral loads were applied to the sample during testing.

The temperature of the sample was maintained constant by circulating an ethylene glycol mixture through the copper cooling coils mounted in the cell. The cooling coils act as heat exchangers and thus maintain the paraffin oil surrounding the sample at a

constant temperature. The temperature was maintained constant by circulating the fluid through a Hot Pak constant temperature bath. The temperature of the paraffin oil surrounding the sample was also measured at the sample mid-height. The temperature of the sample was taken as the oil temperature, since all heat would be conducted radially outward from the cell. The base of the cell was separated from the loading frame using a block of Bakelite, rather than a cooling plate. It was designed in this fashion to reduce the number of constant temperature cooling baths which were required for the experimental program. The outward flow of heat from the cell reduced the temperature fluctuations of the samples.

The measuring instruments used were a LVDT, and a temperature measuring probe. The Hewlett Packard 24 DCDT LVDT was capable of measuring deformations accurately to 0.0013 mm. The thermistors were calibrated using a quartz thermometer which measured the fluid temperature surrounding the thermistor probe to a temperature of .001^{o}C thus the probes would be accurate to 0.01$\pm$.005^{o}C.

(ii) Procedures

The cell containing the constant stress sample was placed on the Bakelite platen and centered. The lines for circulating the ethylene glycol mixture were attached to the cooling coils in the cell. The temperature measuring probe was placed in the oil at approximately mid height of the sample. The constant temperature bath was checked to ensure that the ethylene glycol mixture was at the appropriate temperature and the variable resistor was locked to maintain this temperature. The pump on the bath was started and the fluid allowed to circulate through the cooling coils. The insulated cabinet containing the cell and sample was sealed, and the sample allowed 24 hours to establish an equilibrium temperature. The LVDT was also attached to the power supply and housed in the insulated cabinet to allow it to establish an equilibrium temperature.

In order to reduce the equipment required, four constant stress cells were attached to one constant temperature bath. Thus, in order to have each sample at an equilibrium temperature, no experiment was started until each sample attained an equilibrium temperature. Each sample was ready for testing when the equilibrium temperature was established in all four cells.

The load transfer to the sample was via a lever and dead load system. This required that the various components of the loading system be assembled and that the load be applied to the lever. The assembly of the loading frame and the load transfer system required a certain time, therefore no attempt was made to obtain the instantaneous elastic deformation of each sample.

The load transfer ram with the LVDT and thermistor holder was placed on the steel ball on the upper load platen. The ram was attached to the hanger which transferred the load from the lever to the ram. The load of the hanger and the ram were applied to the load platen (a seating pressure of about 5 kPa). At this point the LVDT was zeroed, the reading was recorded both manually and on the Techtran cassette recorder. The temperature measuring probe was moved to the sample mid height and the reading recorded. The above procedure required that the insulated cabinet be opened for a period of time. Therefore, the box was resealed and the sample temperature allowed to re-establish itself. This time allowed the upper platen to become seated under the low seating pressure and ensured that the temperature of the same was re-established. During this period of approxiamtely one hour, the deformation of each sample was recorded on the cassette recorder at time intervals of ten minutes. The change in the LVDT reading during this time was negligible and therefore this was not considered as part of the sample deformation. The temperature was monitored to ensure that it remained constant and then the sample was ready to have the total load applied.

The load to be applied to each sample had previously been determined so that a pre-selected constant stress would be applied on each sample. The weights were selected and placed beside the load frame on the floor. The load transfer frame was adjusted to ensure that it was in line with the lever transfer pivots in order that the load was applied vertically. Time zero was now established and the LVDT reading recorded. The lever arm and hanger were applied and the LVDT and time recorded. The load was then placed on the hanger and the vertical deformatin and the time were recorded. This load transfer operation required about 30 seconds.

The vertical deformation of the sample was recorded at one minute time intervals using the manual scan of the data acquisition system. The lever arm of the loading apparatus was monitored to ensure that it remained level. This was determined using an oil-filled spirit level and any necessary adjustments could be made by adjusting the screw on the load transfer assembly. The data recording interval was increased to ten minutes after one

hour. This allowed the recording of the reading to be made on the Techtran cassette recorder attached to the data acquisition system. Ten minute recording intervals were continued for a period of 24 hours.

For the duration of each experiment the LVDT and temperature probe readings were recorded at one hour intervals using the Techtran recorder. The recorded data were reduced using a Fortran program and plotted on a Calcomp bed plotter.

The computer processed data were plotted while the experiment was running to study the characteristics of the displacement (strain) versus time plot. Each experiment was continued until the displacement time plot showed an inflection point and accelerated deformation rate. The load was removed when the tertiary mode of creep was well defined but before instability of the sample occurred.

The cell was not disconnected from the constant temperature bath at this point because this would change the equilibrium temperature regime of the other samples connected to the constant temperature bath. The unloaded sample was not removed from the cell. Thus, it was allowed to undergo stress relief. This required the final thin sections and final dimensions of the sample be taken when all the constant stress samples attached to the circulating bath were unloaded.

3.4.4 Creep Tests Using Extension, Bending and Shear

G. Aas (1981) gives brief procedures used to perform creep testing with each of the above analysis and these are included below. Vyalov (1965) also discusses shear creep tests using both conventional direct shear and wedge type shear apparatus. The equipment is described previously, Section 3.3.3-b. Vyalov notes that shear creep tests follow the general procedures outlined for uniaxial creep tests.

A. Extension Tests (After G.Aas 1981)

After freezing a 400 mm long piece of a 54 mm diameter sample, one attached special end caps. The specimen was first mounted in one of the end caps and the conic section was filled with remoul-

ded clay. This clay was then given appropriate time to freeze before the other end cap was mounted in the same way. The middle portion of the specimen was then trimmed to a smaller diameter with the help of a knife and a propane torch. During the extension test the specimen hung from the upper end cap and was loaded by dead weights attached to the lower cap.

The total axial elongation of the specimen was observed with the help of two dial gauges fixed to brass rods as shown in Fig.3.4.12. From this recorded value the relative axial strain ϵ_a, of the restricted mid-portion of the specimen was calculated from the following:

$$\epsilon_a = \frac{\epsilon}{L_1 + (D_1/D_2)^2(L_3 - L_2) + (D_1/D_2)(L_2 - L_1)}$$

B. Bending Tests (After G.Aas 1981)

In the bending tests the specimen was 400 mm long and 54 mm in diameter. The loading and bearing arrangement as shown in Fig.3.4.13 caused a constant bending moment and zero shear stress along the mid-portion of the specimen. The maximum deflection at the middle of the beam was recorded with a dial gauge.

As the stress distribution over the cross-section of the specimen is unknown, there exists some uncertainty connected with the interpretation of the bending tests.

C. Shear Creep Tests

(i) After Vyalov (1965)

Vyalov (1965) states that for testing frozen soils for long term strength and creep in shear, a standard soils direct shear apparatus may be used but will have to be reinforced for testing frozen soil. In certain instances, however, such reinforcement may be insufficient, e.g. to obtain the complete diagram of the shear of frozen soil at low temperatuers for rapid test, etc. In such cases he recommends the use of a wedge type shear apparatus, as shown in Fig.3.4.14.

This apparatus allows shear tests at large values of normal load (T_n) but may not be applicable for small values of T_n. Reasonably good agreement between shearing resistance characteristics obtained on both of the above apparatuses have been determined empirically (Vyalov 1965).

Vyalov's discription of the wedge apparatus is given below:

> The wedge apparatus (Fig.3.4.14) consists of two grips, in which a cylindrical sample is inserted. The lower grip is fixed; the upper (to which the load is applied) is movable, and shears the sample along a plane which passes through its vertical axis. The load on the upper grip is applied vertically, but as a result of the inclined position of the sample, it is decomposed into a normal component σ_n and a tangential component τ_n. The angle α may be changed by removable metal wedges, which yield different relationships between the normal and the tangential stresses. Thus, on the wedge apparatus, the values of the normal and tangential stresses are not assigned arbitrarily, but rather depend upon the value of the total load and are determined as follows:
>
> $$\tau_n = p \sin \alpha ,$$
> $$\sigma_n = p \cos \alpha ,$$
>
> where $p=\frac{P}{F}$, P is the load applied, F is the area of the shear surface, and α is the angle between the surface of the sample under shear and the horizontal.
>
> The load is transmitted to the sample by a press during the tests performed with the wedge apparatus.

(ii) Shear Tests (After Aas,1981)

> These tests were run on specimens trimmed, prior to freezing, to a size of 37 x 37 mm in cross-section area and 100 mm in length. During the tests the specimens were placed between three steel plates as shown in Fig.3.4.15 and loaded in an oedometer load frame. The relative movement between the upper plate and the two lower ones is observed by means of a dial gauge.
>
> Measured deformations, δ, are expressed in percent of the height of the specimen. It should be emphasized that penetration of the steel plates into the frozen soil would cause some uncertainty with respect to the observed deformations. The specified shear

stress, τ, is calculated by dividing half of the total load, P, by the cross-section area of the specimen.

(iii) Simple shear creep tests as reported by J.W.Weaver and N.R.Morgenstern (1981)

(a) Apparatus

Three identical sets of apparatus were constructed to permit simultaneous testing of 3 different frozen soils. Each set consisted of a loading frame, 5 linear voltage displacement transducers (LVDT's), 1 thermistor, and 2 aluminum plates 20.3 x 7.6 cm.

The frozen soil sample (20.3 x 7.6 x 10 cm high) was sandwiched between each pair of plates. The loewr plate was held in an encastre position and the upper plate was subjected to both constant horizontal shear and vertical normal loadings. Horizontal creep displacements of the upper plate and the frozen soil at intermediate points between the plates were monitored in the direction of applied shear. Vertical creep displacements of the upper plate were monitored in the direction of normal loading. Hewlett Packard 24 DCDT LVDT's monitored deformations to an accuracy exceeding 0.0001 cm.

Normal loads were imposed by a direct hanger system to which weights were applied. Shear loads were maintained by an adjustable pulley system to which weights were applied. A schematic layout of the apparatus is presented in Fig.3.4.16.

The 3 creep cells were located inside a controlled environment laboratory where ambient temperatures were maintained between $-2^{o}C$ and $-3^{o}C$. Sample temperature fluctuations were further reduced by enclosing the apparatus in a large insulated box and circulating ethylene glycol from a constant temperature bath through pipes in the plates. This technique reduced short term temperature fluctuations to $\pm 0.5^{o}C$. Sample temperatures were monitored directly by freezing a thermistor into a pre-drilled hole at the centre of each sample. The thermistors were calibrated at the outset and on completion of the test program to an accuracy of $\pm 0.01^{o}C$, using $\pm 0.001^{o}C$ quartz thermometer.

Output signals from the LVDT's and thermistors were monitored and recorded at 6 hr. intervals using a data acquisition system. Information obtained included a record of vertical and horizontal deformations, and temperature as a function of time.

(b) Procedure

The following preparation was identical for all frozen soil samples.

The cylindrical specimen was removed from the PVC mould and trimmed in the ice laboratory on a milling machine. The finished sample was 203 mm long x 76 mm wide x 100 mm high. The 2 aluminum test plates were cleaned and thoroughly rinsed in distilled water, dried, and frozen to the top and bottom of the specimen. A thin coating of water droplets was sprayed onto the 4 exposed faces of the sample, and a moist sheet of Saran Wrap was wrapped around the entire sample to effect an air-tight seal in order to reduce desiccation of the sample during testing. The shafts of two 25 mm long flathead nails were frozen into 2 pre-drilled horizontal holes. The nails were located 5 mm above the bottom plate and 5 mm below the top plate. They provided a stable monitoring datum, against which the 2 LVDT's were to be placed. The exact positions of the 2 nails and the upper plate with respect to the lower plate were recorded. A thermistor was frozen into a pre-drilled 2.5 mm diameter hole which extended to the centre of the sample.

The sample was then assembled within the loading frame and placed within the insulated test housing unit. Hoses from the constant temperature bath were connected to swagelock fittings on the 2 plates and ethylene glycol was circulated through the pipes in the plates. Two LVDT's were positioned vertically, at either end of the top plate and 3 LVDT's were positioned horizontally, against the 2 nails and the upper plate. The shear loading pulley was adjusted to impart horizontal shear loading to the top plate and the normal loading hanger was assembled around the sample.

The 3 apparatuses wre positioned beside one another within the insulated housing unit and allowed to stand for either 48 hr or until thermal equilibrium was attained within the samples.

Normal loading and then shear loading were applied instantaneously with the aid of a rigid platform and 2 hydraulic jacks.

(iv) Simple shear creep tests were performed on ice samples by D.C.C. Sego (1980)

(a) Apparatus

The simple shear tests were performed in a cell designed and constructed for this purpose. The detials of the cell and loading system are shown in Fig.3.4.17. The basic principle of the testing system is illustrated in Fig.3.4.18 which shows that a normal load and a shear load are imparted to the upper platen and then transferred to the sample via a set of serrated grip plates on the top and bottom of the sample.

The cell and loading apparatus was constructed in the workshop of the University of Alberta. A shear load can be applied to the upper load platen. This causes a shear distortion within the sample which can be measured by measuring the horizontal displacement of the upper load platen. The shear load is applied by a horizontal ram which passes through a Thomson linear bearing in the cell wall. A constant load is applied to this horizontal rod by passing a steel cable attached to the rod over a pulley and placing a dead weight on this hanger. The total shear load is measured by a load cell attached to the loading ram and the upper load platen within the cell. The horizontal load is transferred into a shearing stress applied to the sample by a serrated plate between the upper load platen and the top of the sample, Fig.3.4.18. This serrated plate is melted into the sample to ensure that it is in intimate contact with the ice.

The vertical load is applied to the sample through a vertical loading ram which passes through the top of the cell cover. This load is transferred to the upper load platen through a set of roller bearings which allow the load platen to move horizontally without placing a lateral thrust on the sample. Temperature was controlled by cooling coils within the cell. Twenty-four hours were allowed for the sample to reeach the equilibrium temperature.

b) Procedure

The horizontal and vertical LVDT's were attached to the loading rams, and a zero reading taken. The total dead load required to apply the constant vertical stress was applied on the vertical hanger system. The shear load was placed on the shear load hanger to impart a constant shear stress on the sample. The zero time was recorded and the zero reading of the horizontal LVDT, and the vertical LVDT and the shear load cell were recorded. The

temperature at the mid-height of the sample was also recorded. The reading of each of the above recording devices was taken at one minute intervals for the first hour. The recording interval was increased to ten minutes for the next 24 hours, and then one hour thereafter. The data was recorded automatically on the Techtran cassette recorder. The recorded data were processed using a Fortran computer program.

The computer processed data were plotted throughout the experiment to determine the displacement versus time plot for the sample. The experiment was stopped after the displacement versus time plot showed a steady state portion or when tertiary creep was established.

3.4.5 Sample L:D Ratio and End Preparation

One area in which there does not appear to be any consensus among researchers concerns the allowable sample L:D ratio and sample end cap interface conditions. Vyalov (1965) recommends a sample L:D ratio of at least 2.0-2.5 and states that lubricating the sample end planes is not permissable.

Ladanyi and Arteau (1978) however, state the following:

> Quite a different view of the sample problem, however, has been taken in compression testing of essentially plastic materials, such as metals, plastics and unfrozen soiils. Since these materials fail in a plastic manner, they are less sensitive to stress concentration at the ends. However, many of them fail at relatively high strains, and since they retain a large portion of their strength after failure, it is of great practical interest to follow their behaviour also in the post-failure region up to large strains.
>
> At large strains, however, friction is mobilized between the specimen ends and the conventional steel platens, restraining the ends from lateral extension and leading in general to a non-uniform distribution of stresses and strains in the sample, formation of dead zones at the ends with barrelling in the center, and an increase in measured axial compression strength. One possible solution to this problem seems to be the use of lubricated end

> platens, consisting of one or two layers of silicone grease and thin rubber membranes. Studies have confirmed, in general, that the use of enlarged lubricated end platens, prevents the formation of the dead end zones, and allows the testing of shorter samples, which deform much more uniformly than long samples, and which tend to retain their cylindrical shape even at large post-failure strains. In addition, these shorter samples have a tendency towards multiple-failure surfaces and general plastic distortion failure, rather than the premature development of a predominant failure surface.
>
> The lubricated platens as described above, result in a very low friction at the specimen ends and enable measure of an approximately correct axial compression strength of the material. Another, alternative, solution consists in expecting some friction to develop at the platens and in making a proper correction of the load at large strains.

Roggensack (1977) in creep tests on natural permafrost samples, used a maximum sample length of 12 to 13 cm with 10 cm diameter cylinders in order to ensure relatively uniform ice structure within each sample. An overhead milling machine was used to trim the sample ends parallel.

Roggensack states that:

> Since specimen lengths were less than the normally adopted minimum of twice the diameter, it was felt that lubricated load platens should be used to reduce end friction during the tests. Previous research has shown that using friction reducers at either end of short soil specimens is an effective means of duplicating strength results obtained in tests with conventional sample lengths (Rowe and Barden, 1964; Duncan and Dunlop, 1968). Lubricating the load cap and base pedestal required the use of centering pins to restrain the specimen from lateral movement following the application of axial load. Shallow holes drilled in either end of the creep specimens accepted pins which had been fixed at the center of each load platen.

Details of Roggensack's end lubrication method are shown on Fig.3.4.19.

Aas (1980) performed uniaxial creep tests on specimens 54 mm in diameter and 40 mm in height between two aluminum end platens. The author does not comment on any influence of his L:D sample ratio and end cap configuration on measured strength.

Both Alnouri (1969) and Alkire (1972) used sample L:D ratios of 2.0 and friction reducers on the end caps. Alnouri's friction reducers consisted of a sheet of aluminum foil coated on both sides with a thin layer of silicone grease. A thin polyethylene film was then applied to both sides of the aluminum foil and excess grease and entrapped air were worked out with a straight edge. Alkire formed friction reducers by sandwiching two layers of polyethylene and a greased aluminum disk at each end of the sample.

Savigny (1980) testing natural permafrost samples used L:D ratios not less than 1.5 and not greater than 3.0. The base plate and load cap on his apparatus were both teflon coated.

Shuster (1971) cored natural permafrost test samples from larger diameter field cores using vaporized liquid nitrogen as the drilling fluid. Coring was done using a high quality industrial drill fitted with diamond core barrels. The configuration of the diamond matrix and vents on the core barrel were varied for the type of soil being cored. Sample end trimming was done using a conventional mason's saw with table and guide. The author states that for triaxial type testing no special treatment was required other than the coring and cutting described above. No special end cap treatments were used.

3.4.6 Triaxial Sample Jacketing

In testing conducted using a constant temperature bath, samples are generally protected by standard rubber membranes. Roggensack (1977), however, found that:

> Initial attempts to use conventional natural rubber membranes with aqueous solutions of methyl alcohol or ethylene glycol were not successful. While these fluids satisfied the necessary freezing point depression criterion, they invariably caused chemical damage to the membrane. The cracking, blistering and crazing often resulted in small amounts of leakage which were sufficient to damage the sample. Direct leakage and diffusion occurring through the rubber produced significant amounts of ice corrosion and sample deterioration over the lengthy test durations required.
>
> To decrease the risk of aborting a test in its terminal stages, light paraffin oil was used to apply confining pressures within the creep cell. Although the oil was messy to work with, it caused no visible adverse effects. Laboratory trials were conducted to assess the potential for intrusion into the soil during prolonged tests. As part of this preliminary study, cell pressures were elevated well beyond the range intended for use in the creep tests. No intrusion was observed during these trials so the paraffin method of applying confining pressure was adopted. As an added precaution, a spray bottle was used to apply a thin coat of ice to all of the test specimens before placing them in contact with the oil.

In ice testing, polyurethane jacketing can be wrapped around the sample (personal communication, W.Bawden, tti Geotechnical Resources Ltd., February, 1983). Various rubber membrane materials are given in Table 3.4.1.

3.4.7 Discussion

Most researchers follow the general guidelines set out by Vyalov. Long-term creep tests are generally performed on lever or dead weight test frames. Temperature control is achieved either by conducting the complete test in a walk-in cold room with very strict temperature control or by enclosing the test sample in a controlled temperature bath. Test systems vary somewhat between laboratories and also depending on the particular nature of the tests being performed.

TABLE 3.4.1 RUBBER MEMBRANE MATERIALS FOR TRIAXIAL TESTING AT LOW TEMPERATURES

PROPERTY @ 22°C	Natural	Neoprene	Butyl	Silicone	Nitrile	ASTM Tests	Rating
Tensile Strength (MPa)	17-24	21-28	17-21	4-9	3-6	D 412	A - Excellent
Tear Resistance	A	C	C	E	D	D 624	B - Very Good
Resilience	A	B	E	B	C	D 945, 1054	C - Good
Aging Resistance	A	A	B	A	D-C	D 572, 573	D - Fair
Cracking Under Stress	D	B	C	A	E	D 581, 1171, 3395	E - Poor
Low Temperature Flexibility	A	C	C	A	C	D 746, 797, 1053	
Minimum Service Temp (°C)	-50	-40	-45	-115	-50	-	
Chemical Resistance						D 471	
Silicone / Kerosene / Paraffin — Oil	E	C	E	E	A		
Ethylene Glycol	C	B	B	B	C		
Sodium Chloride (25%)	D	B	A	D	B		

References

(1) The Vanderbilt Rubber Handbook (1978), R.O. Babbit, Editor, R.T. Vanderbilt Co. Inc., Norwalk, CT.

(2) Rubber and Plastics Research Association of Britain Data Handbook (1971).

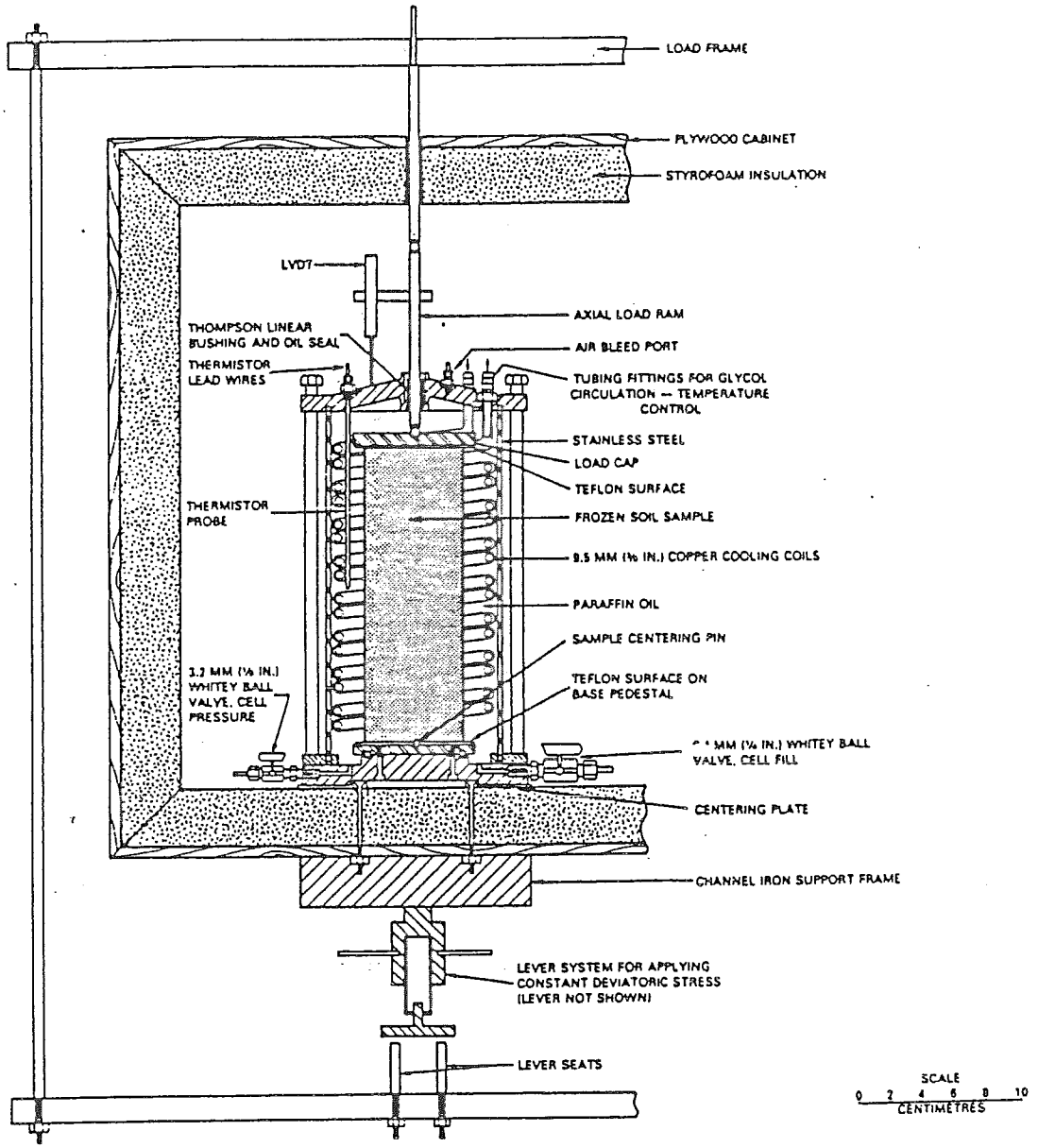


FIGURE 3.4.1 Schematic Layout of Specially Designed Triaxial Cell Used for Creep Tests. (after Savigny, 1980)

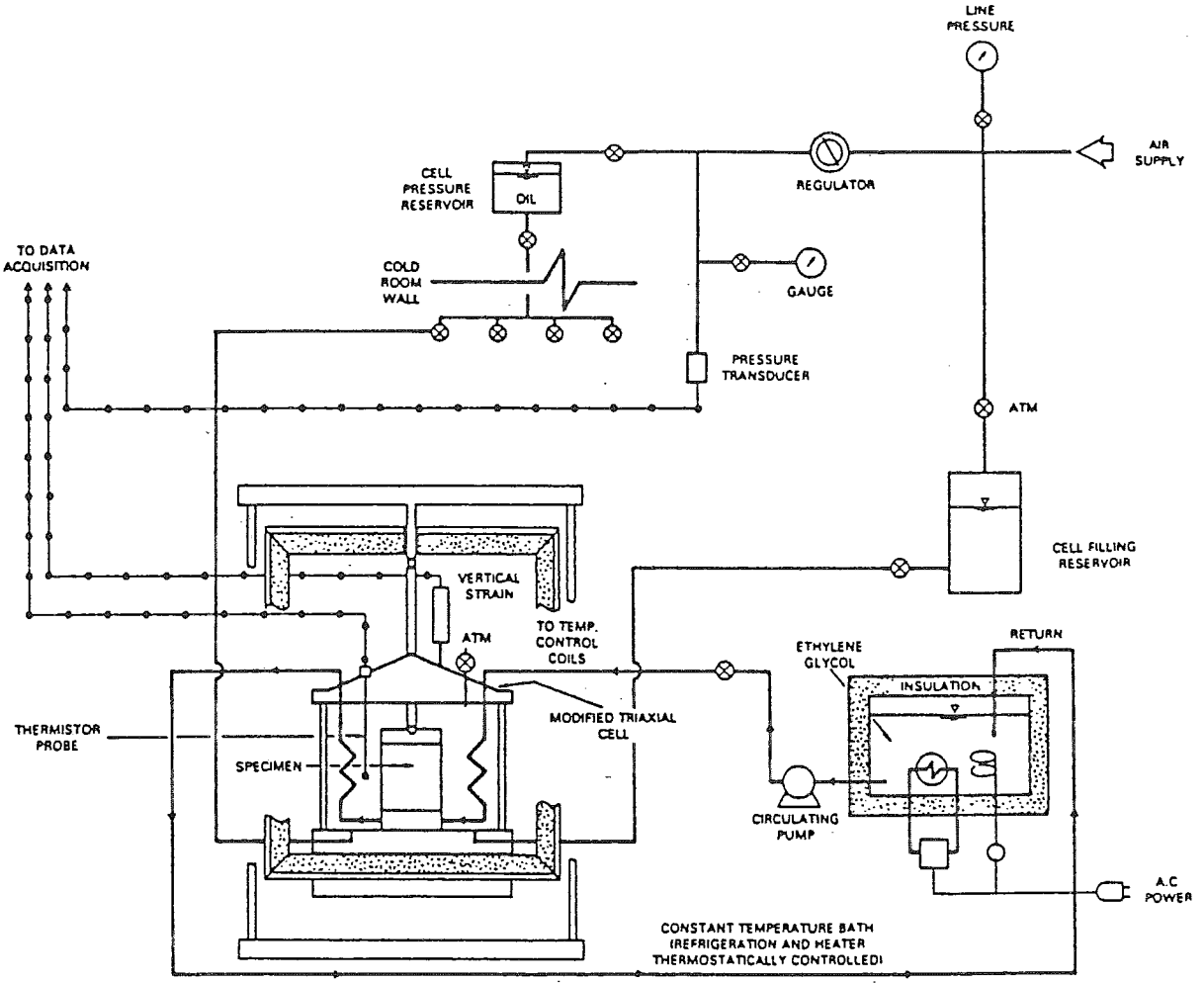
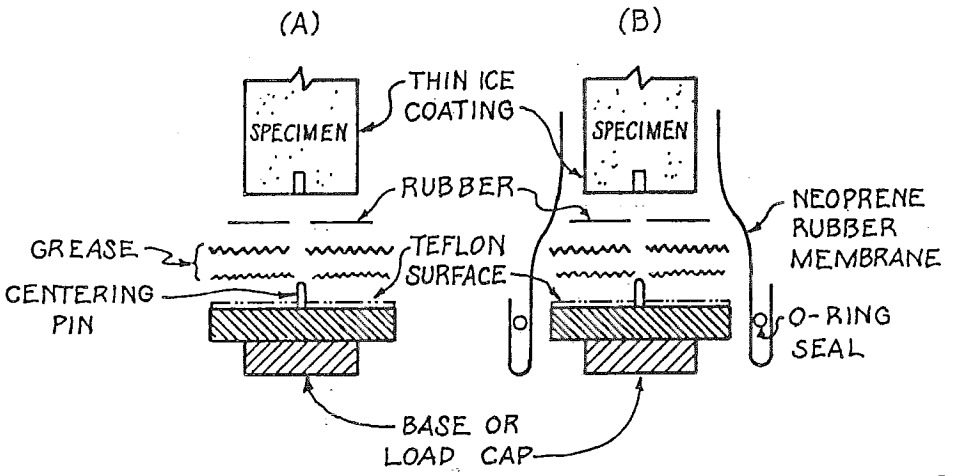


FIGURE 3.4.2 Schematic Layout of Creep Testing System.
(after Savigny, 1980)



Grease consists of a coat of Dow-Corning high vacuum covered by a molybdenum disulphide lubricant preparation.

FIGURE 3.4.3 Detail of Alternate Methods of End-Lubrication Employed in Creep Tests. (after Roggensack, 1977)

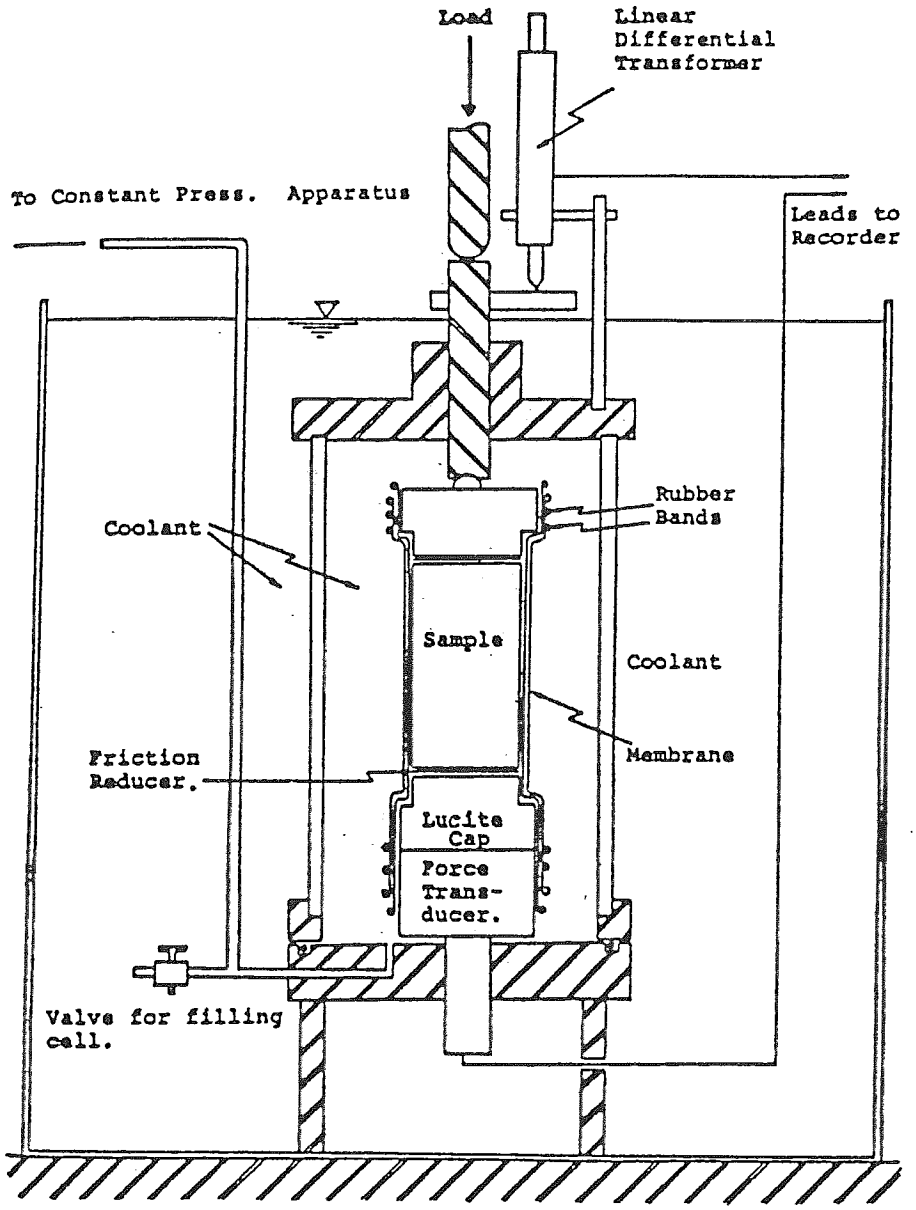


FIGURE 3.4.4 A Schematic Diagram of the Sample Placement in the Triaxial Cell. (after Alnouri, 1969)

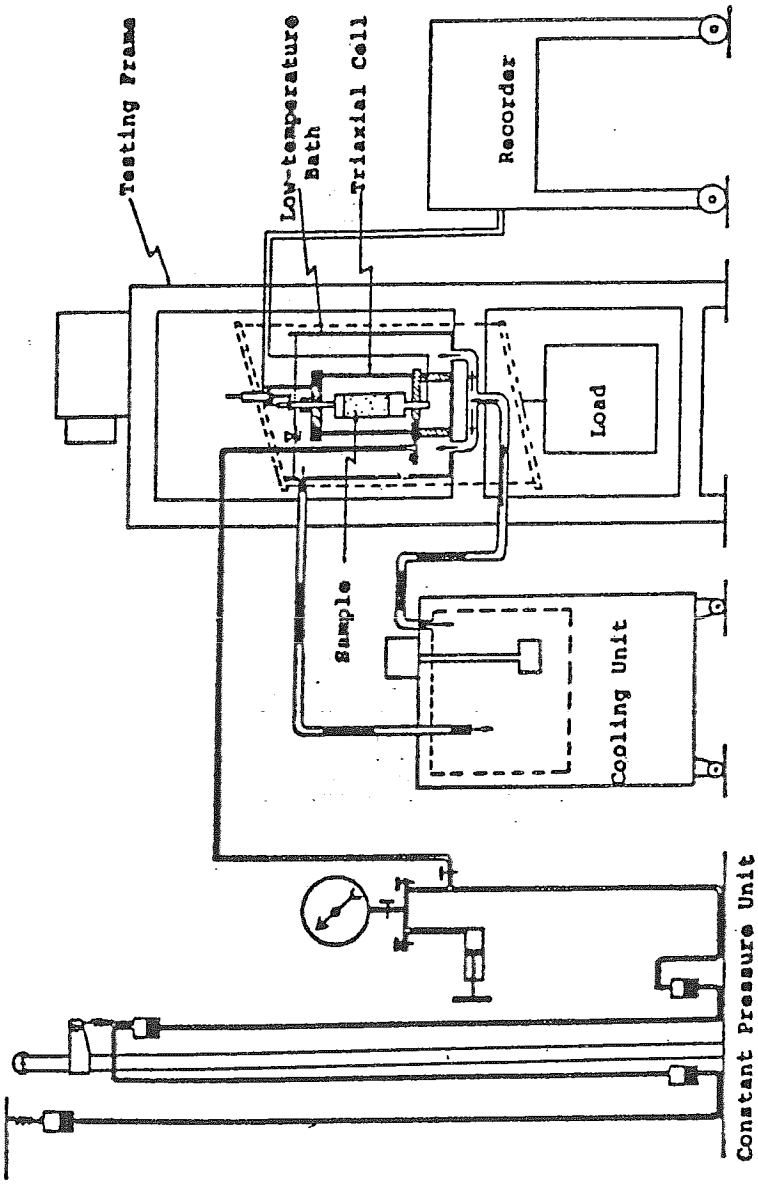


FIGURE 3.4.5 Diagramatic Layout of the Testing Apparatus.
(after Alnouri, 1969)

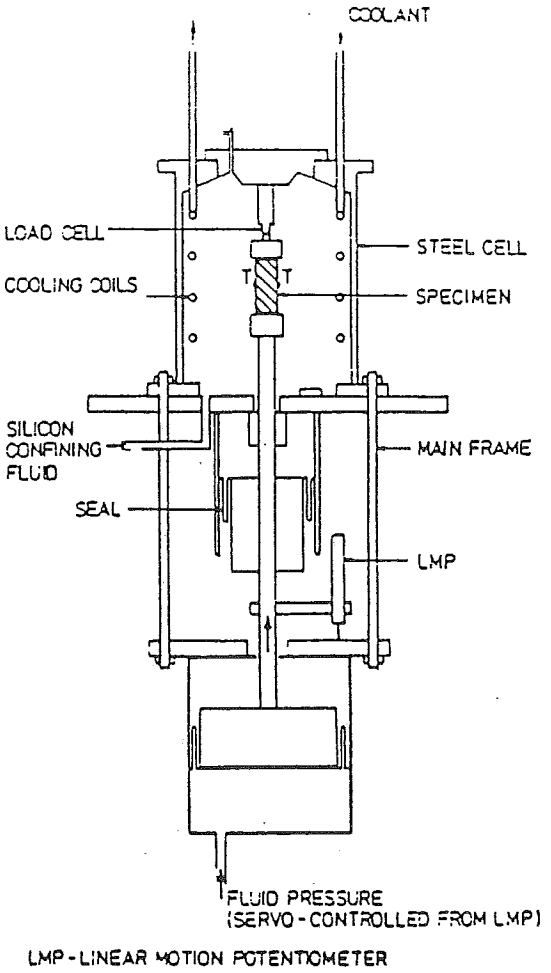


FIGURE 3.4.6 Schematic of Testing Apparatus. (after Gardner, et al, 1982)

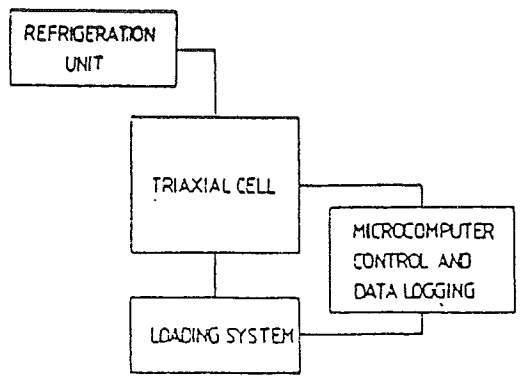


FIGURE 3.4.7 Block Diagram of Main Components. (after Gardner, et al, 1982)

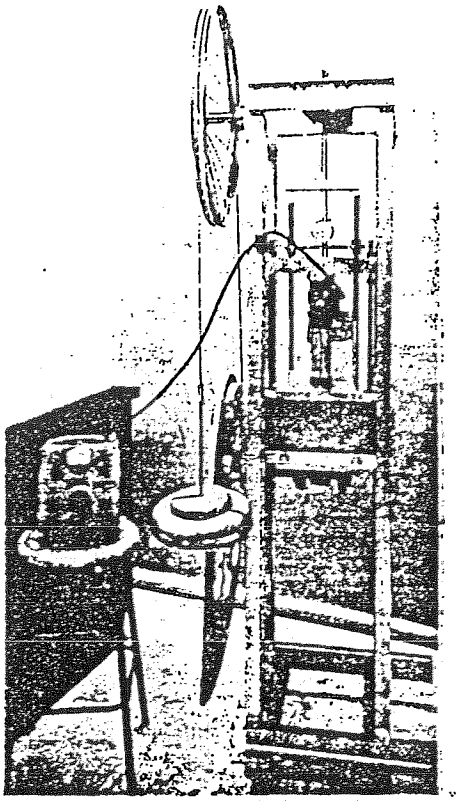


FIGURE 3.4.8 Constant Stress Apparatus Showing Programming Cam and Load Measuring System (after Sayles, 1968).

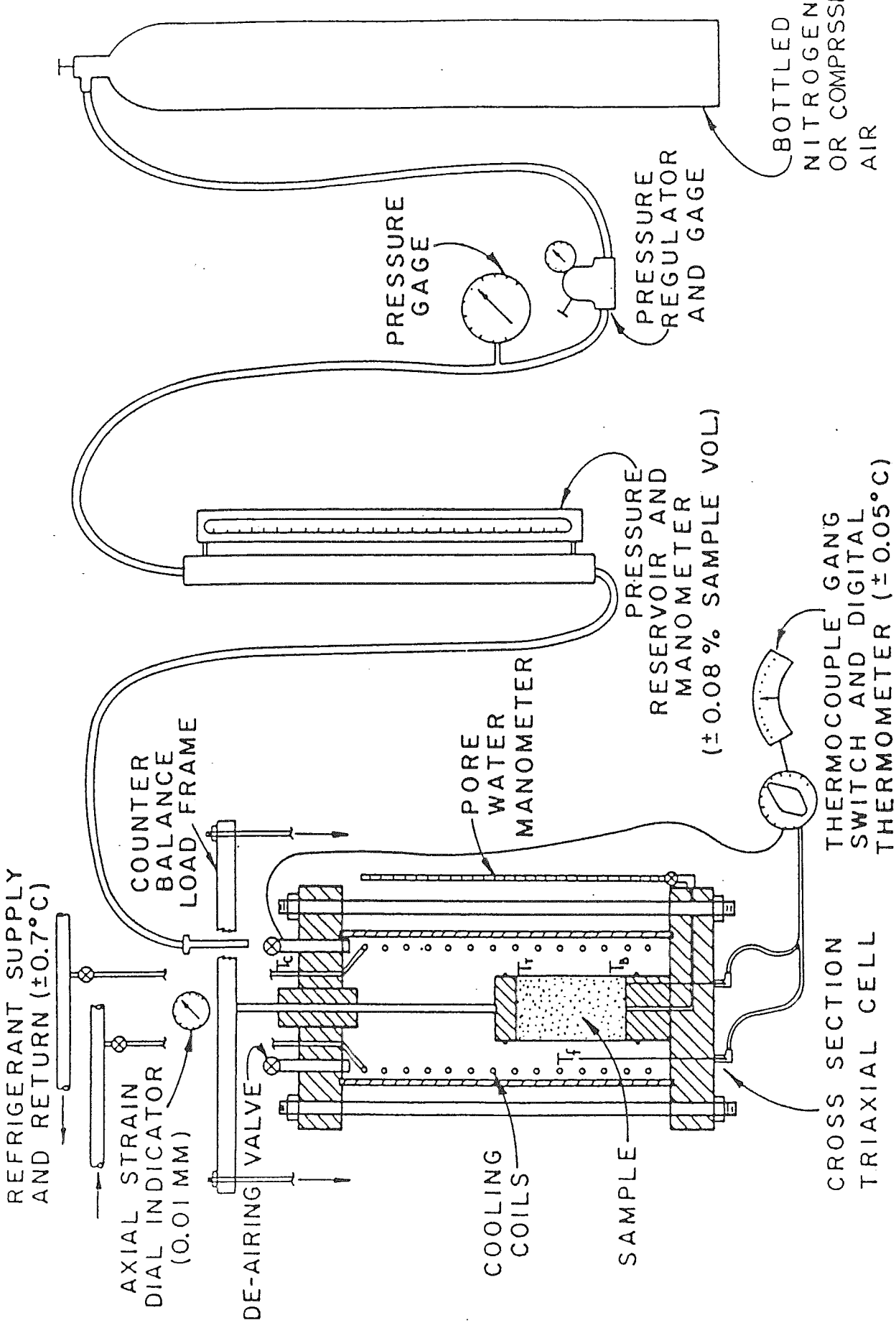


FIGURE 3.4.9 Schematic of Refrigerated Triaxial Cell System. (after Shuster, 1981)

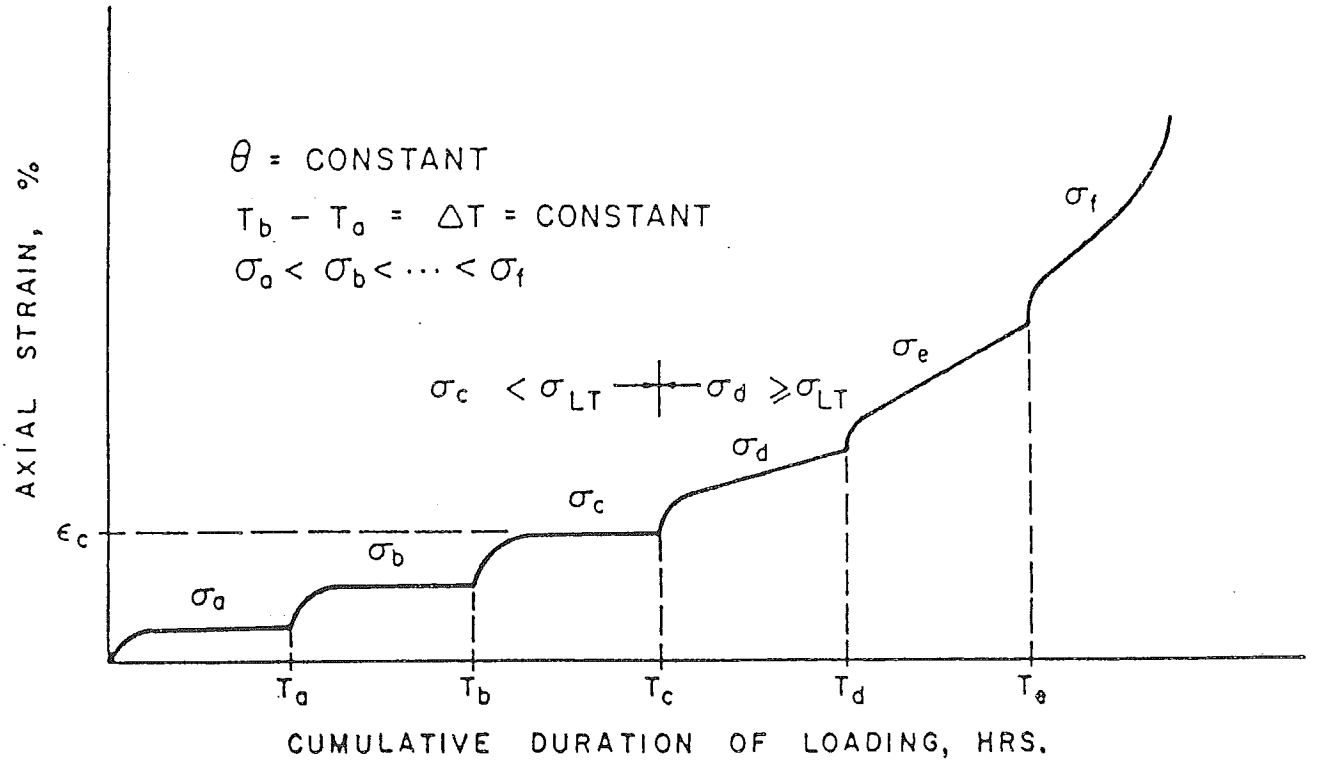


FIGURE 3.4.10 Determination of Yield Point from Incremental Test Data. (after Shuster, 1981)

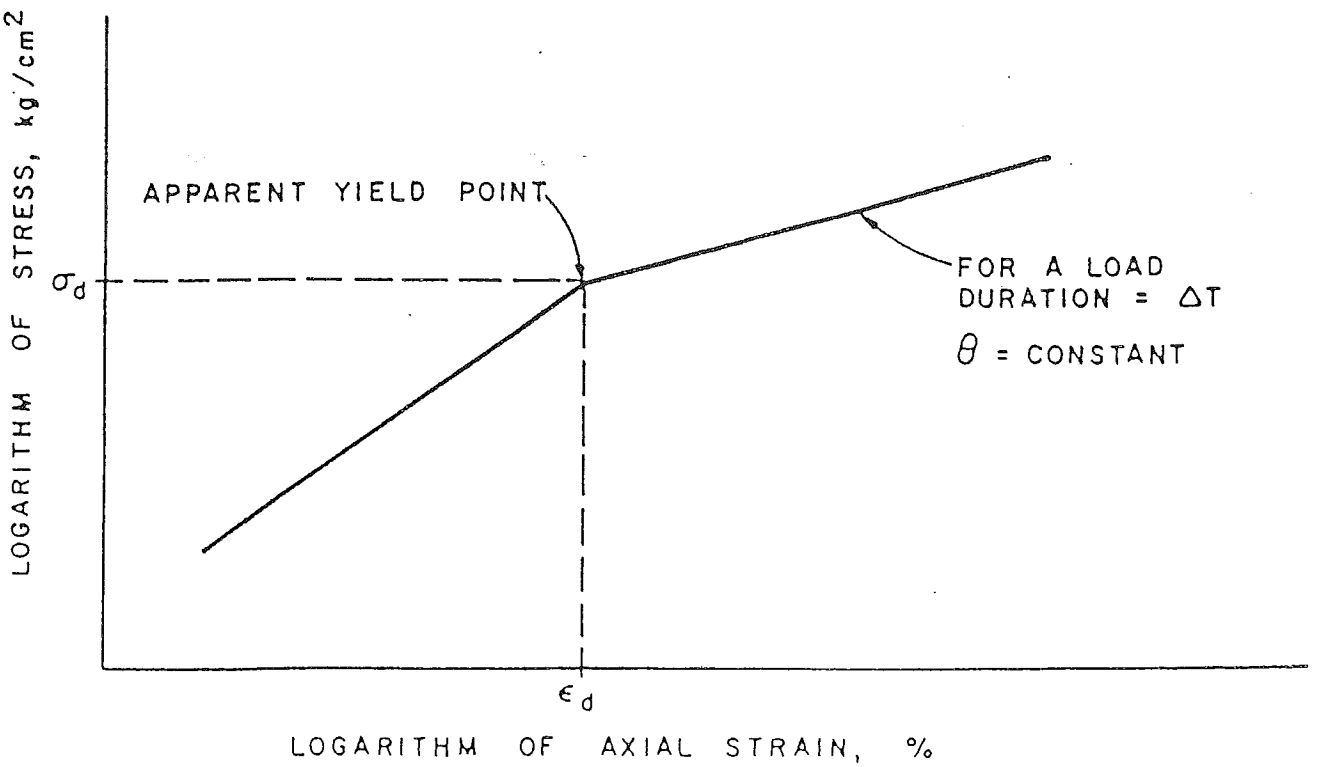
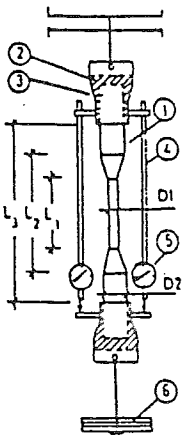
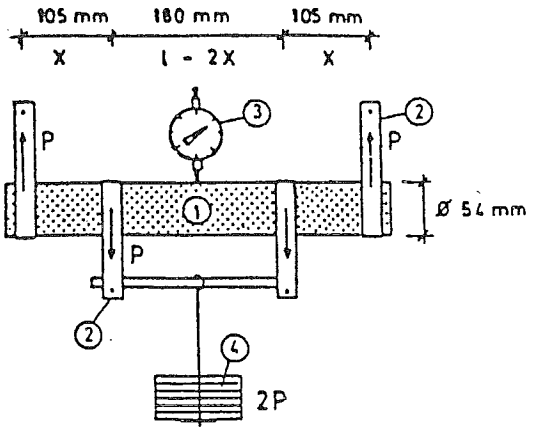


FIGURE 3.4.11 Determination of Yield Point from Incremental Test Data. (after Shuster, 1981)



1 = frozen clay specimen; *2* = remoulded and thereafter frozen clay; *3* = fixed-end cap; *4* = brass rod; *5* = dial gauge; *6* = dead weights.

FIGURE 3.4.12 Extension Test Device. (after Aas, 1980)



1 = frozen sample; *2* = metal strap; *3* = dial gauge; *4* = dead weights.

FIGURE 3.4.13 Bending Test Device. (after Aas, 1980)

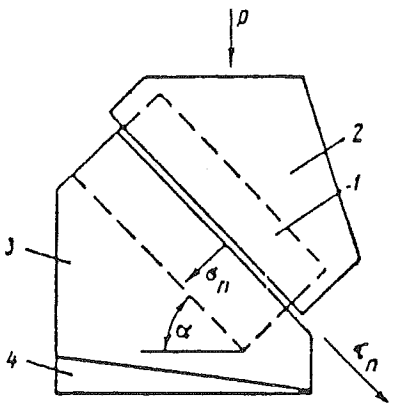
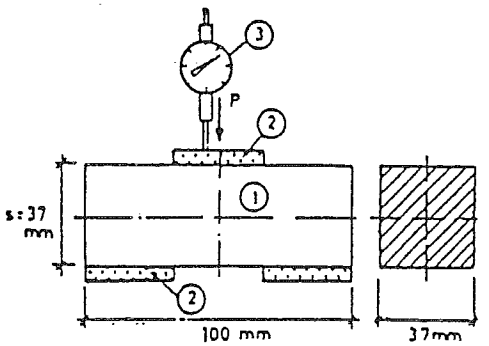


FIGURE 3.4.14 Diagram of the Wedge Block Apparatus
(1) cylindrical sample
(2) moving grip
(3) fixed grip
(4) wedge block

(after Vyalov, 1965)



1 = frozen specimen; *2* = steel plates; *3* = dial gauge.

FIGURE 3.4.15 Shear Test Device. (after Aas, 1980)

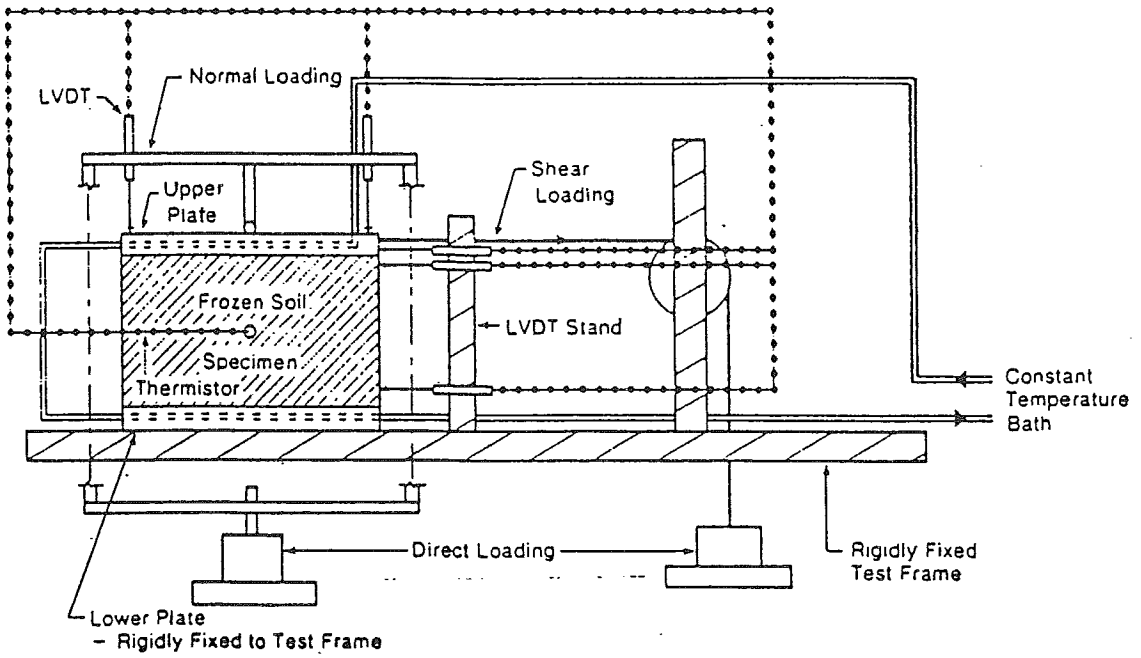


FIGURE 3.4.16 Schematic Layout of Simple Shear Experiments (after Weaver and Morgenstern, 1980)

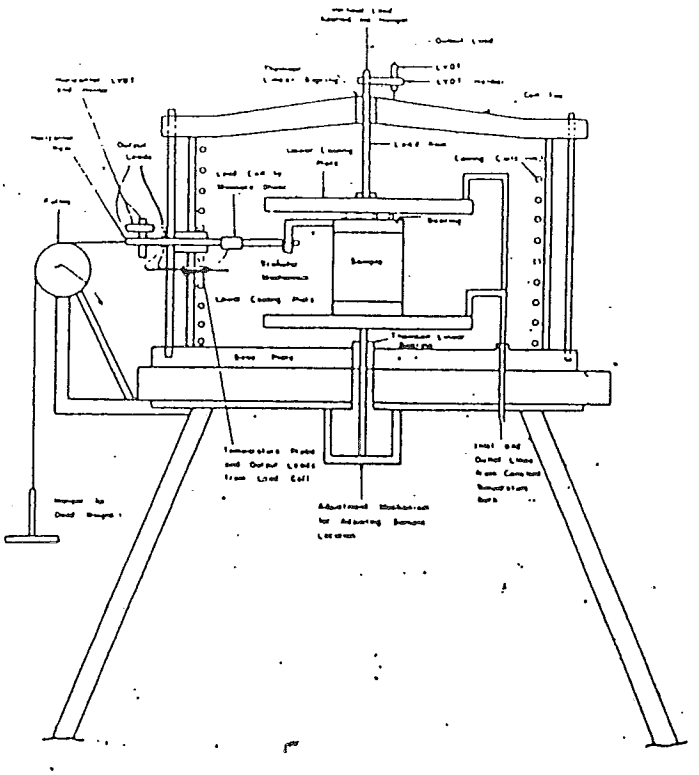


FIGURE 3.4.17 Simple Shear Loading System. (after Sego, 1980)

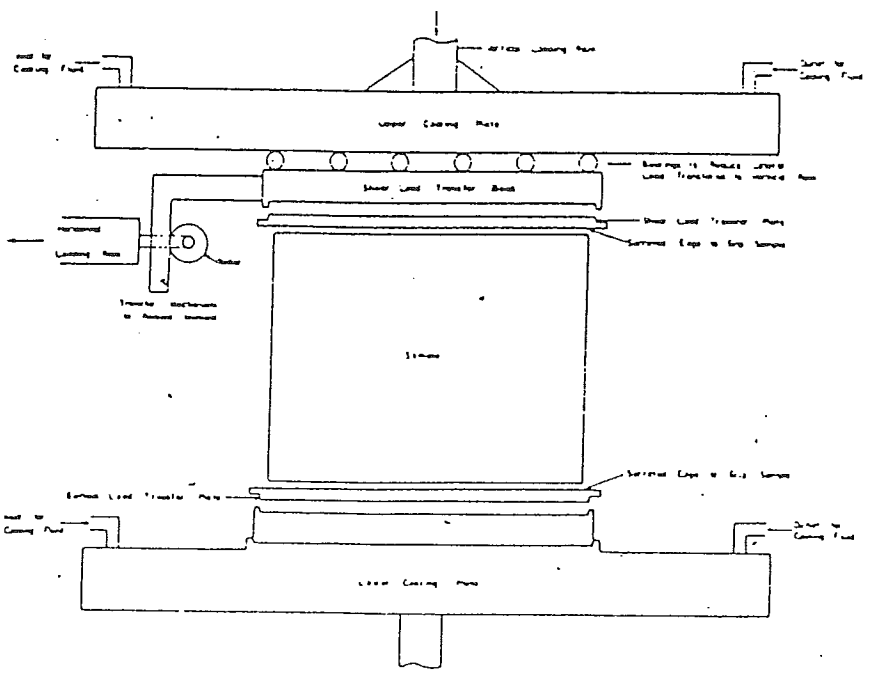


FIGURE 3.4.18 Detail of Loading System in Simple Shear Experiment. (after Sego, 1980)

3.5 DYNAMIC PROPERTIES

3.5.1 Introduction

Foundations for structures incorporating vibatory loads (e.g. providing support for heavy machinery such as turbines) present special problems. Magnifications of motions due to structural resonances, fatigue, consolidation, etc. result from vibratory loading and are complicated by the presence of frozen and/or thawing soils. The response of such soils to vibratory loads differs significantly from that of normal unfrozen soils and this response needs definition.

Ground surface motions that occur during earthquakes are also influenced to a large extent by the characteristics of the underlying soil deposit under dynamic loading. Present analytic techniques to predict ground surface motion require knowledge of the dynamic shear modulus and damping ratio.

Methods of assessing the dynamic stress-strain and damping characteristics of frozen soils under high frequency loading conditions are discussed by Kaplar (1969) and Stevens (1973). Procedures for assessing the dynamic properties at lower frequencies (i.e. typical of strong motion earthquakes) are described by Jessberger (1972) and Vinson (1975, 1978). Youssef (1981) describes an apparatus and testing procedure to evaluate the effect of vibrations on creep behaviour of frozen ground.

At present, very limited dynamic testing has been done on permafrost materials. Apparatus and test procedures derived from the literature are described below.

3.5.2 Testing at CRREL

3.5.2.1 C. W. Kaplar (1969)

Kaplar used non-destructive laboratory dynamic tests to study the elastic properties of frozen soils and ice. Vibrations were induced in laboratory made beams of frozen soil and ice by electromagnetic means. His laboratory apparatus and test procedures are given below:

(i) Test Equipment

Dynamic modulus test apparatus The principal items of equipment used in this investigation are shown in Fig.3.5.1. The complete apparatus consisted of a variable frequency oscillator capable of producing frequencies from 18 to 220,000 cycles per second, an amplifier, a cathode-ray oscilloscope, a vacuum tube voltmeter, and a magnetically coupled specimen vibrating apparatus and detector. The magnetically coupled vibrator was designed and constructed for this study by Dr.Francis Birch of Harvard University. Beams having dimensions of approximately 1 1/2 x 2 1/2 x 11 inches were used in the investigation. The vibrator, however, can accommodate beams up to 2 1/4 in. square in cross section.

Permanent bar magnets, 3/16 x 3/16 x 2 in., were frozen flush into horizontal grooves prepared in each end of the frozen specimen beams with the ends of the magnets protruding 1/4 inches on each side. Vibration of the specimens was actuated by two oscillating magnetic fields from a pair of electromagnets mounted in series at one end of the apparatus. Each electromagnet consisted of very fine wire wound around a C-shaped laminated core. The air gaps between the poles of the magnets were 1/4 inch, sufficient to accommodate the 3/16 inch thick bar magnets without touching.

The electromagnets were held in horizontally and vertically adjustable supports and could lie in either a horizontal or a vertical plane. A switching arrangement was provided to enable corresponding poles of each electromagnet to be of the same or of opposite polarity. The arrangement of the two detector magnets on the other end of the apparatus was the same as on the driving end.

Preparation of frozen specimens for testing After freezing, the specimens were removed by carefully dismantling the tray. The appearance and a brief description, including size and fre-

quency of ice lenses, were recorded. Each specimen was trimmed to uniform dimensions, measured, weighed, and tempered for a period of at least 16 hours at each test temperature before sonic testing.

(ii) Test Procedures

The specimens, with bar magnets frozen-in horizontally across each end, were supported by their sides in a horizontal position in the apparatus between pairs of posts with blunt cone-shaped prongs. For longitudinal and torsional vibrations, the beam was supported midway between the ends. For flexural vibrations, the beam was supported at the 'quarter nodes', a distance from each end equal to 0.224 times the length of the specimen.

The two driving electromagnets were positioned so that each projecting end of the bar magnet embedded in the test beam lay between the poles of an electromagnet.

Since the poles of the electromagnets change polarity with the frequency of the alternating current in the coils, they alternately attract and repel the permanent bar magnet, causing the specimens to vibrate. The position of the two driving electromagnets, the direction of the current in their respective coils, and the position of the specimen support(s) determine the type of vibration that is induced.

For flexural and torsional vibrations, the electromagnets were set so that their poles were in the same vertical plane as the bar magnets on the specimen. To produce flexural vibrations, the alternating current was made to pass through the coils so as to produce polarities of opposite sign in the corresponding poles of the two driving electromagnets. The resulting simultaneous attraction and repulsion of the bar magnet in an up and down direction caused the beam to vibrate in flexure. To incite torsional vibrations, the beam was supported firmly at its midpoint and current passed through the driving magnets. This caused the specimen to vibrate in torsion about its longitudinal axis. Longitudinal vibrations were produced with the poles of the electromagnets placed in a horizontal plane, with corresponding poles having opposite polarity, the specimen being supported at the midpoint. The effect was alternately to push and pull on the bar magnet in a horizontal plane, parallel to the longitudinal axis of the specimen.

The permanent bar magnet at the opposite end of the beam was caused to vibrate at the same frequency and the fluctuations of the magnetic field induced an electromotive force of varying intensity in the receiving or detecting coils. In theory, the

peak voltage is induced when the specimen is vibrating at its natural frequency and the amplitude of the vibrations is then at a maximum. The fundamental resonant frequency was detected with a vacuum tube voltmeter and/or a cathode oscilloscope connected to the detecting coils, and read from the dial markings of the calibrated oscillator. Peak readings on the voltmeter and oscilloscope were also obtained from overtones or harmonics of the fundamental frequency. In the torsional and longitudinal modes, the overtones are nearly integral multiples of the respective fundamental frequencies. In the flexural mode, the frequencies of the first two overtones occur at 2.7 and 5 times the fundamental frequency.

The following equations (Pickett, 1945) were used in the computations:

Flexural vibrations. $E_f = CW(f_t)^2$

(A value of 1/3 was assumed for Poisson's ratio , to find C from curves given in Pickett, 1945. The value of is not critical and the assumption is reasonable.)

Longitudinal vibrations. $V_L = 2f_L L$

and $$E_L = \frac{w(V_L)^2}{g} \quad \frac{4wL^2(f_L)^2}{g}$$

Torsional vibrations. $V_t = 2f_t L$

and $$G = \frac{w(V_t)^2 R}{g} \quad \frac{4wL^2 R(f_t)^2}{g}$$

(R is 1.183 for a square prism (Pickett, 1945)).

Correction to observed frequencies for mass of magnets (Rayleigh, 1929).

Flexural vibrations: $f_t = f_t \left(1 + \frac{2M}{w}\right)$

Longitudinal vibrations: $f_L = f_L \left(1 + \frac{M}{w}\right)$

Torsional vibrations: $f_t = f_t \left(1 + \frac{K}{w} M\right)$

Poisson's ratio. Poisson's ratio is computed from E and G using the relation:

$$\nu = \frac{E}{2G} - 1$$

It should be remembered that these formulas are strictly applicable only to an isotropic elastic solid complying with Hooke's law.

3.5.2.2 H. W. Stevens (1973, 1975) CRREL

Stevens performed laboratory tests where a right cylinder (i.e. with upright axis perpendicular to base) of frozen soil was subjected to steady state sinusoidal vibration in the longitudinal or compressional mode and, again, in the torsional or shear mode. Testing was conducted in a walk-in cold room where temperature could be controlled to $\pm 1^{o}C$. The objective of the study was to provide reliable values of the stiffness and damping properties and to define significant factors affecting these. Testing was done on laboratory manufactured samples. Test apparatus and procedures are described below.

(i) Apparatus

A vertical cylinder of soil is subjected to steady-state sinusoidal vibration at its lower or base end with the other end free except for a light, relatively rigid cap. The input and output stress waves are observed and measured with piezoelectric accelerometers attached to the base plate and cap plate at each end of the specimen. The peak acceleration and the frequency are recorded. The drive frequency may be any value above the so-called "rigid body frequency" and within the limits of the drive motors, if the phase angle between input and output waves can be accurately measured; otherwise, the specimen must be excited at a known resonance. The ratio of output to input amplitudes, and the frequency, together with the specimen properties of density and length, are required to compute the desired parameters.

The complete test apparatus includes the device for applying vibration shown schematically in Fig.3.5.2 and the control and readout apparatus shown schematically in Fig.3.5.3.

A steel drive base, having suitable provisions for attaching accelerometers for measuring longitudinal and torsional motion in g's is bolted to a steel drive shaft. The shaft is supported in a heavy steel framework through wagon-spoke-type springs and is attached to the electromagnetic motors. A light steel cap has provision for attaching accelerometers, one on the longitudinal

axis and two on the circumference, to measure the torsional motion.

The readout instrumentation receives the two accelerometer signals from the top and bottom of the sample and, after amplification of the signals, feeds them through a phase meter, a dual-channel tracking filter, a dual beam oscilloscope, digital voltmeters, an electronic counter (frequency meter), a logarithmic converter, and a Z-Y recorder, as shown in Fig.3.5.3.

(ii) Test Procedures

The specimen is carefully weighed and measured before freezing to the baseplate and cap of the test apparatus. The calibration of the voltmeters is accomplished as follows: the sensitivity of the particular accelerometer (in pico coulombs/g) is set on the sensitivity dial of the variable gain charge amplifier (the amplifier should have this capabilitiy such as the Kistler Model 503). A 1.00-peak volt signal (0.707-volt root-mean-square (rms) as read on the voltmeter) at approximately 5000 Hz is applied at the CAL INPUT connector. The OUTPUT is monitored on the sensitive voltmeter. This output, which corresponds to 1 g, can be adjusted by the gain on the charge amplifier. Thus, depending on the accelerometer sensitivity and on the operating range, the gain can be set such that 1 g = 1 v, or 1 g - 0.1 v, etc.

Most of the tests to date have been conducted using a resonating specimen and, although the off-resonance method using the phase meter is currently in use, data are still taken at the resonant frequencies. The procedure is as follows: the operator applies the vibration in either the longitudinal or torsional mode with the drive force at a low level (top acceleration of 1 g or less) and sweeps the frequency upward. As the frequency is swept, attention is directed to the X-Y recorder. The ouputs from the charge amplifiers and tracking filter are then fed through the logarithm converters. The log of the bottom acceleration is subtracted from the log of the top acceleration. The difference (acceleration-amplitude ratio) is applied to the Y-axis of the X-Y recorder. The 'Record' output of the frequency meter is applied to the X-axis of the recorder. Thus, a printed record is obtained of acceleration ratio vs. frequency. The frequency of maximum amplitude ratio (or acceleration ratio) can be easily located and the resonances enumerated, since the second, third and fourth resonances are approximately multiples of 3, 5, and 7, respectively, of the first resonance. With the pen of the plotter set on the first resonance point, the frequency is recorded together with the two g values from the voltmeters. The drive force is increased a significant amount and the procedure is repeated. The frequency is then changed to the second resonance, the readings at the various drive forces are repeated, etc.,

through the fourth and fifth resonances. The drive mode is changed, longitudinal to torsional, or vice versa, and the series of readouts is repeated.

To employ the nonresonance method, the procedure is the same except that the phase is measured and the X-Y recorder is not required. The operator selects an initial frequency and applies the vibration, in either mode, with the drive force again at a low level. The outputs from the charge amplifiers are switched into the phase meter, measuring the phase lag between the bottom and top accelerations. The frequency is recorded together with the two g values and the phase angle. A range of drive forces is applied and the readings are recorded for each force, after which the next required frequency is set, etc. until the range of frequency desired is covered.

3.5.3 Testing in West Germany

3.5.3.1 H. L. Jessberger (1972) Ruhr-Universitat, Bochum F.R.G.

Jessberger performed dynamic triaxial shear tests to simulate dynamic ice loads working against a protected frozen soil body forming part of an offshore arctic production island. This test apparatus and procedure are given below (Jessberger and Jordan, 1982).

(i) Apparatus

For the tests for simulating the above described in situ conditions the special triaxial shear apparatus 'TSW-Apparatus IIb' is used. In Fig.3.5.4 this apparatus is shown schematically together with the peripheral modules. The servohydraulic actuator operates in a closed loop system which recently was introduced into materials testing. The actuator (4) is loading the frozen sample (5) vertically, and the system works in the following way:

High pressure oil from the power pack (9) is delivered through a servo valve (3) to the hydropulse actuator (4) which in return loads the soil sample (5). The test force is measured in the form of a voltage by a load cell (6) and its associated signal conditioner (7). The output of the displacement transducer (6a) installed in the base of the actuator is used as control parameter. In the servo controller (2) the feedback signal is continuously compared with a command signal which is produced by the

function generator (1). The power amplifier (2a) converts the resulting difference into the control signal for the servo valve (3). The function generator (1) produces sine, triangular and square wave forms.

The system is connected with parameter readout and recording units. The data of displacements are recorded by multichannel recorder or by tape (8). With periodic signals the peak values are stored and displayed at the digital display unit (8a).

The frozen soil sample with 10 cm diameter and 20 cm length can be loaded vertically by a maximum stress (static or dynamic) of 5 MPa and horizontally by a static cell pressure of max. 1 MPa. The limit frequency of the system depends on the magnitude of the dynamic load and of the piston amplitude. Testing frozen soil the limiting frequency can reach at the most 60 to 80 Hz.

The sample is frozen with the help of a twinwall tube (13). In the space between the two tube walls the coolant is circulating. To make the heat transfer from the twinwall tube to the cell fluid easier, at the inside of the wall many curves are cut to increase the contact surface. It was found in preliminary tests that this system leads to constant temperature fields around the frozen soil sample. At three points outside the soil sample the temperature was measured using thermistors with the result that the requested tmperature is constant within a tolerance of $\pm 0.2^{o}C$.

(ii) Procedure

The saline soil sample already in a frozen condition is placed into the triaxial shear apparatus and subjected to a sinusoidal dynamic axial loading. Fig.3.5.5 shows schematically a triaxial test result. The dynamic stress leads to a cyclic vertical strain ε. $\Delta\varepsilon_{el}$, the difference between the maximum ε_{max} and minimum ε_{min} vertical strain, is called the elastic strain. The Modulus of dynamic deformation is given by the following relation:

$$\tilde{E} = \frac{\Delta\sigma_v}{\Delta\varepsilon_{el}}$$

3.5.4 Testing at Michigan State University

3.5.4.1 Vinson et al (1975, 1978)

The studies performed by Vinson et al were aimed at developing a testing system and methods to evaluate the dynamic properties of frozen soils over a range of test conditions which simulate earthquake loadings of permafrost deposits.

In evaluating a test system Vinson gives the following criteria:

1) temperature control over a range 0 to $-10^{o}C \pm 0.1°C$

2) control of confining pressure over a range 0 to 1400 kN/m^2 ± 10 kN/m^2

3) control of strain amplitude over a range 10^{-3} to 1 percent, and

4) control of frequency over a range 1 to 5 Hz.

At the onset of the rsearch work it was decided to couple existing equipment to evaluate the dynamic properties of unfrozen soils with existing temperature control equipment to evaluate the static properties of frozen soils. It was felt that this approach would significantly expedite the development of a test system to evaluate the dynamic properties of frozen soils.

The strain amplitude and frequency range of interest in the test program dictate that only three dynamic test devices be considered:

1) cyclic triaxial,
2) cyclic simple shear, and
3) cyclic torsional shear (Hollow Cylinder Samples).

Temperature control of frozen soils during testing can be achieved by employing any one of three methods:

1) placing the test equipment (all or part) in a cold room or einvironmental chamber;
2) circulating a coolant in a cold bath around a cell containing the frozen soil specimen and noncirculating coolant; or

3) circulating coolant through a coil placed around the frozen soil specimen which is inside a cell containing a noncirculating coolant.

Vinson (1978) gives a detailed evaluation of the relative merits of the various tests, existing equipment and temperature control methods. He concludes that:

> The cyclic triaxial device has the advantage of being a more conventional piece of test equipment than the torsional shear device. A greater backlog of information exists for this test device than for the cyclic torsional shear device. This could prove to be a valuable asset in the overall research program. Further, it would be easier to prepare an artificially frozen solid cylindrical specimen than it would be to prepare a hollow cylindrical specimen. Naturally frozen core specimens could be tested directly with the cyclic triaxial equipment, whereas the cores would have to be hollowed out for the torsional shear device. For these reasons, it was decided to couple the cyclic triaxial test equipment with the cold bath to evaluate the dynamic properties of frozen soils.

(i) Description of Cyclic Triaxial Test Equipment

Figures 3.5.6a and b show a schematic diagram of the cyclic triaxial test system developed in the research program. The test system consists of four basic components:

1) An electrohydraulic closed-loop test system (actuator, servovalve, hydraulic power supply, servovalve controller, hydraulic controller, and function generator) which applies a cyclic axial load (deviator stress) to the frozen specimen.

2) A triaxial cell which contains the specimen and non-circulating coolant.

3) A refrigeration unit and cold bath which circulates the coolant around the triaxial cell.

4) Transducers, and output recording and monitoring devices (load cell, spring-actuated gauge head with a linear variable differential transformer (LVDT), thermistors, strip-charge recorder, digital multimeter, and storage oscilloscope) to monitor the load (stress) and displacement (strain).

(ii) Electrohydraulic Closed-loop Test System

The heart of the test setup is the electrohydraulic closed-loop test system. It consists of a commercially available 0.010 m^3/min , 20700 kN/m' hydraulic control unit with a function generator, a servovalve controller with command and feedback signal conditioning, and a 5000 kg actuator with a 0.057 m^3/min servovalve. Referring to Fig.3.5.6c, the system operates as follows:

1) A command signal (voltage) from the function generator or other external source is input to the servovalve control unit where it is compared with the feedback signal (voltage) from a transducer (a load cell or LVDT) monitoring the response of the specimen in the closed loop.

2) The difference (error) between the two signals is amplified and applied to the torque motor in the servovalve coupled to the actuator.

3) The torque motor drives a pilot stage which in turn drives a power stage of the servovalve, which directs hydraulic fluid under pressure to one side or the other of the double-sided actuator piston to cause the actuator to move.

4) The movement of the actuator causes the specimen to respond in such a way that the transducer monitoring the specimen 'feeds back' a signal equal to the command signal.

The speed at which these steps are executed causes the specimen, for all practical purposes, to be subjected to a loading equal to the command signal.

(iii) Triaxial Cell

A schematic of the triaxial cell inside the cold bath is shown in Fig.3.5.6b. The cell is 180 mm in diameter and 350 mm high. An aluminum cell was chosen over steel or Lucite for three reasons:

1) It has sufficient strength to allow testing at high confining pressure (compared with Lucite).
2) It is lightweight for ease of handling (compared with steel).
3) It has a higher thermal conductivity (compared with steel and particularly with Lucite) to insure that the noncirculating coolant inside the bath remains at a temperature approximately equal to the coolant circulating outside the bath.

Two thermistors were attached to the 71 mm diameter and 1.8 mm high specimen to monitor its temperature during the test. An LVDT in a spring-actuated precision-gauge head was attached across the specimen to the cap and base to monitor displacement. The output of this LVDT was also the feedback signal in the closed loop. A load cell attached to the base plate of the cell monitors the load.

When the spring-actuated gauge head LVDT is mounted at the side of the specimen, care must be taken to insure that tilting of the specimen cap or base does not influence the LVDT displacement reading. A device developed in this research program to eliminate any error associated with tilting is shown in Fig.3.5.6d. It consists of three basic components:

1) A base clamp (attached to the specimen base) with a connecting rod for the gauge head body and a connecting rod to the cap assembly.
2) An anti-tilt ring connected to the cap assembly connecting rod with a piece of spring steel. The anti-tilt ring has a diameter 6.3 mm greater than the specimen cap to allow free movement about the cap. It has a screw-adjustable bearing plate which contacts the gauge head probe shaft.
3) A cap clamp (attached to the specimen cap) attached to the anti-tilt ring with two spring steel leaves.

The spring steel leaves between the anti-tilt ring and the cap clamp act as a pivot point. Any (slight) tilt of the specimen cap will not be transmitted through the spring steel. As the specimen cap moves, the probe shaft of the gauge head in contact with the bearing plate is forced to move because the anti-tilt ring is fixed to the base clamp with the cap assembly connecting rod. The movement at the pivot point causes the displacement measured at the gauge head to be twice that of the specimen at the centerline. (This is another advantage of the anti-tilt assembly...it effectively doubles the output of the LVDT for a given specimen displacement).

The two thermistors used to monitor temperature of the specimen were calibrated with a laboratory thermometer with a scale division of $0.1^{o}C$. The thermistors were capable of reading to the nearest $0.1^{o}C$. The temperature of a specimen was obtained by averaging the readings of the two thermistors.

(iv) Cooling System

The cold bath is approximately 0.35 x 0.35 x 0.46 m and contains 0.48 m^3 of circulating coolant, excluding the volume of the triaxial cell. The bath was constructed so that the coolant

enters at the bottom and returns to the refrigeration unit from a line at the top of the bath. It is important to insulate the top of the cold bath as this represents a potential source of heat loss in the cell (and specimen through the cell top plate). Two 25 mm thick sheets of styrofoam were used for this purpose. In addition, coolant was "washed" across the top plate of the cell through an auxiliary circulating line. With these precautions it was found that the temperature inside the cell adjacent to the specimen did not vary appreciably along the length of the specimen.

To ensure that thermal equilibrium had been reached in the specimen and the coolant surrounding it in the cell, temperature measurements were made at the center of ice and frozen clay specimens and adjacent to the specimen, as shown in Fig.3.5.7. The figure illustrates the variation of temperature as a function of time for three test conditions. In one test (Fig.3.5.7a) an ice specimen and stainless steel cap and base were at an initial temperature of $-16^{o}C$ and the coolant inside the cell was at a temperature of $-12^{o}C$. After approximately one hour, the temperature of the specimen (measured with a thermistor frozen in the center of the specimen) and the coolant inside the cell were equal and remained constant. Similar results were obtained when an aluminum cap and base were used with an ice specimen (Fig.3.4.7b) and when a stainless steel cap and base were used with a clay specimen (Fig.3.5.7c).

The temperature of the coolant in the refrigeration unit was controlled by a mercury thermometer thermostat submerged in the coolant. The temperature difference between the cold bath and refrigeration unit was approximately $0.5^{o}C$ as shown in Fig.3.5.7a, b, and c. Therefore, it was possible to set the thermostat in the refrigeration unit and obtain any test temperature desired with reasonable accuracy. The average temperature in the specimen did not vary by more than $\pm 0.1^{o}C$ during a test.

(v) Output Recording and Monitoring

The maximum deviator stress and axial strain were evaluated by measuring amplitude of the load and displacement trace on the strip-chart recording obtained during a test, and dividing by the cross-sectional area and length of the specimen, respectively. The damping ratio was evaluated from the photographic record of load versus displacement obtained with the storage oscilloscope. Specifically, the area of the hysteresis loop, A_L , was measured with a planimeter from an enlargement of the photographic record, and the work capacity per cycle was determined by measuring the amplitude of load and displacement from the enlarged record. A

digital multimeter was used to monitor the voltage ouput from the load cell and LVDT and thermisotr resistance during the test as required.

The frequency response of the strip-chart recorder was checked and it was determined there was no variation in the amplitude of the input signal when the frequency was varied from 0.05 to 50 Hz. There is no variation in the amplitude of the input signal to the storage oscilloscope over a much greater range of frequency. In this respect the storage oscilloscope has a great advantage over an x-y recorderfor which there can be significant mechanical hysteresis for frequencies greater than 0.3 Hz.

The signal from the load cell and LVDT has 'noise' at very low voltage output. This 'noise' was not visible on the traces on the strip-chart recorder; however, it was recorded on the storage oscilloscope. To eliminate the 'noise', the input signals to the storage oscilloscope were filtered. Extreme care was taken to avoid any 'phase offset' between the channels. However, the filtering caused some attenuation of the input signals. The attenuation appeared to be somewhat dependent on frequency. Consequently, the dynamic Young's modulus could not be determined from the hysteresis loop recorded with the storage oscilloscope without many calibrations. To avoid these calibrations, only damping ratio was determined from the hysteresis loops recorded. This could be done because damping ratio is a non-dimensional parameter.

During the latter stages of development of the test system a minicomputer was used for on-line, real-time data processing. As expected, this afforded significant time savings in the data reduction effort. For example, it took one day's computational effort to reduce and check the rest results 'by hand'; it took 1/2 hour of additional testing time to reduce and check the test results with the minicomputer. However, the strip-chart recorder and storage oscilloscope are still employed to obtain permanent records of the analog output from the load cell and LVDT.

Specimen Preparation and Specimen Coupling Device Cylindrical specimens 71 mm in diameter and 178 mm in height were tested in the research program. All of the specimens tested were reconstituted materials artificially frozen in the laboratory.

A cohesive unfrozen soil can be subjected only to a very small tensile stress and a cohesionless soil cannot be subjected to any tensile stress. Consequently, cyclic triaxial tests on unfrozen soils are always performed with the specimen in a compressive state of stress. In contrast to this, frozen soils and ice can be subjected to relatively high tensile stresses before failing.

Consequently, it is possible during strain (or stress) controlled cyclic triaxial testing for the specimen to go into tension.

Two possible devices to couple the specimen to the cap and base to achieve a tensile state of stress were considered in the research program. The 'screw' coupling shown in Fig.3.5.8a consists of four screws 6.4 mm in diameter in the cap and base. The 'screw and metal plate' coupling shown in Fig.3.5.8b is essentially the same as the 'screw' coupling except that an aluminum plate, 54 mm long , 25.4 mm wide, and 6.4 mm thick, was attached to two of the screws in the cap and base. The clearance bewteen the cap and the aluminum plate was set at 12.7 mm .

Fig.3.5.9 shows a comparison of the hysteresis loops obtained for an ice specimen without a coupling and for an ice specimen with the 'screw' and 'screw and metal plate' couplings. The hysteresis loop for the specimen without a coupling is highly nonsymmetric. This is reasonable since the specimen can be subjected only to compressive stresses. The hysteresis loop for the specimen with the 'screw' coupling is also highly nonsymmetric. This indicates that (1) the specimen failed, (2) the dynamic modulus in compression is much greater than that in tension, or (3) the coupling was not sufficient to resist the tensile force applied. Inspection of the specimens from the tests with this coupling indicated they had not failed. In the authors' opinion, there is no reason to believe that the modulus in tension for ice is significantly different from the modulus in compression at the low strain levels associated with cyclic triaxial testing. Thus, the hysteresis loop could not be explained on this basis. It was concluded, therefore, the coupling did not provide sufficient resistance to the tensile force.

The hysteresis loop for the specimen with the four screws and metal plate shown in Fig.3.5.9 is symmetric and indicates that resistance to the tensile force was developed which allowed the specimen to be subjected to a tensile stress. This coupling was selected for use in the research program. It is obvious that with the 'screw and metal plate' coupling the effective length of the specimen used to calculate dynamic properties would be slightly less than the total length of the specimen. The effective length of the specimen is extremely difficult to calculate because it is dependent on the dynamic elastic moduli of the specimens. For practical purposes, the effective lengths were assumed to be 25.4 mm shorter than the full length, owing to a reduction of 12.7 mm from the cap and 12.7 mm from the base. If the estimate of effective length is slightly in error, it would result in only a small error in the evaluation of the dynamic modulus and axial strain. The lengths of the specimen were

approximately 180 mm with corresponding effective lengths of 155 mm . If the assumed effective length was ±10 mm in error, the error in the dynamic modulus would be about ±6.5 percent and in the strain about ±7 percent.

(vi) Test Procedure

The frozen specimens were stored in a freezer at -20°C ±1°C after they were jacketed with two rubber membranes, each with a wall thickness of 0.5 mm . Prior to testing, the base clamp of the anti-tilt device was fastened to the specimen base (see Fig.3.5.6d and 3.5.8b). The specimen was immersed in the cold bath and the base was fastened to the load cell (see Fig.3.5.6). The anti-tilt device was assembled as follows:

1) The gauge head body was attached to the connecting rod of the base clamp.
2) The cap clamp was fastened to the specimen cap in a position such that the screw-adjustable bearing plate on the anti-tilt ring bore on the probe shaft and caused the output from the LVDT to be close to zero.
3) The anti-tilt ring (in a horizontal position) was connected to the spring steel extending from the base clamp; the bearing plate was screw adjusted to move the probe shaft to its null (zero voltage output) position.

After the anti-tilt device was attached to the specimen, a collar pressing the thermistors to the side of the specimen was placed around the specimen. The aluminum triaxial cell cylinder was placed on the base plate of the cell. Finally, the top plate was tightened down on the cell cylinder and the piston loading rod was connected to the cap by inserting it through a ball-bushing loading collar. Care must be taken when attaching the piston rod. If the torque applied in tightening the piston rod is too great, the specimen will fail. After the piston rod was attached, the specimen assembly could be checked by manually applying a cyclic vertical load to the piston rod and observing the hysteresis loop. If the loop did not exhibit the symmetric shape shown in Fig.3.5.9c the specimen assembly was not good.

The voltage output from the gauge head LVDT attached across the specimen to the cap and base was the feedback signal to the servovalve controller. With the LVDT in this position, deformations associated with loose connections, elastic deformations of the piston loading rod, or the load frame were eliminated.

When the specimen assembly was satisfactory, the cold bath was covered with styrofoam and an auxiliary coolant line was placed on the top plate of the triaxial cell. A small increase in temperature was usually experienced during the installation of the specimen. Therefore, the specimens were left in the cell for at least two hours to ensure temperature equilibrium in the triaxial cell and specimen before a dynamic test was conducted. The temperatue of the specimen was controlled by the mercury thermometer thermostat in the refrigeration unit. The two themistors attached to the side of the specimen were monitored to obtain the temperature to within $\pm 0.1^{o}C$. If the temperature was not correct, the thermostat was readjusted and the test was delayed two hours to ensure that a temperature equilibrium condition was reached.

After the specimen was installed in the triaxial cell, a test was conducted employing the following procedure:

1) The LVDT in the actuator was used as the feedback signal to move the actuator ram to within 12 mm of the piston loading rod. The hydraulic power supply was turned off and a valve at the supply port of the hydraulic manifold of the actuator was closed to prevent fluid movement.

2) The feedback signal was changed from the LVDT in the actuator to the LVDT on the anti-tilt device. The actuator and the piston loading rod were connected with a split-ring connector, and a confining pressure of approximately 350 kN/m^2 was applied to the specimen to prevent disturbance caused by the movement of the actuator during the reapplication of hydraulic pressure to the actuator. The servovalve stabilitiy adjustments for the closed-loop test system were strongly dependent on the strength of the specimens and "snugness" of the connection. For practical purposes, they were readjusted whenever the movement of the actuator observed on the strip-chart recorder deviated from the command sine wave form.

3) The hydraulic pressure was applied and the valve at the supply port of the hydraulic manifold was opened. The actuator was now controlled by the LVDT on the anti-tilt device.

4) Following Steps 1, 2, and 3 an axial load was generally induced on the specimen. This axial load was monitored on a digital voltmeter. The specimen was returned to a zero axial load (deviator stress) condition by adjusting the command signal voltage level to the LVDT on the anti-tilt device. The LVDT voltage output after this adjustement was nonzero. A voltage offset was used to bring the net LVDT output close to zero so it would stay "on scale" on the output recording devices.

5) The sensitivities of the recording devices were set for the range of frequencies and voltage outputs anticipated during testing. The setting for the load cell could be made from experience after testing a number of specimens.

6) The desired strain (displacement) amplitude and frequency for the test was selected. A sinusoidal wave form was selected as the command signal.

3.5.5 Testing at the University of Calgary

3.5.5.1 H.Youssef et al (1981)

Youssef notes that foundations for structures incorporating vibratory loads in cold regions may significantly change the creep that will occur under static loading. The authors describe the development of an apparatus to study this phenomenon. The apparatus is designed to test simultaneously two specimens subject to identical static compression and temperature conditions. One of the specimens is then subjected to additional torsional vibration at its base, while the top is free to rotate, (modified Drnevich Free-Free resonant column apparatus). An extensive laboratory testing program on frozen soils has not been carried out to date. The experimental apparatus is described below.

(i) Experimental Apparatus

The experiment set-up which was developed at the University of Calgary consists basically of six components -- 1) dynamic creep triaxial cell; 2) static creep triaxial cell; 3) cooling system; 4) static loading system; 5) dynamic loading system; and 6) output reading instrumentation to monitor the static load (axial stress), dynamic response of the specimen and the apparatus (frequency and amplitude of vibration), and the temperature of the specimen.

Dynamic and static creep triaxial cells The dynamic and static creep triaxial cells are almost identical in their configuration and dimensions. The main difference is that the first cell is designed to incorporate the vibration excitation apparatus and the transducers for monitoring the vibration response of the top and bottom (namely passive and active) ends of the sam-

ple. A description of the dynamic cell components is given in detail in Fig.3.5.10 and the corresponding key.

(ii) Cooling system

Five refrigeration units (Hotpack Canada Ltd., Model No.603340) have been used, two for each triaxial cell and one for cooling the cold room which contains the apparatus. One refrigeration unit circulates the cold anti-freeze through the cell base and inner coils which surround the specimens, the second refrigeration unit circulates the cold anti-freeze in the outer coil around the cell. An anti-freeze bath inside the cell has been used to insure uniform temperature around the specimen. Precision thermistors (YSI 44004 Model), are located inside the cap and base plates and, also, around the specimens to monitor the temperature. From long term tests the cooling system has been proved to control the temperature of the specimen in the range of $0^{o}C$ to $-9^{o}C$ with a maximum fluctuation of $\pm 0.2^{o}C$.

(iii) Static loading system

A regulated nitrogen pressure is supplied from a nitrogen tank to a gas reservoir, which was introduced to the system as a precaution against pressure fluctuations; this reservoir is designed and checked for a maximum pressure of 6900 kN/m^2 . The regulated nitrogen pressure was supplied to the pressure cylinders inside the two cells through four pressure lines connected in parallel. Each pressure line is connected to the corresponding gas cylinder, this allows supply of identical nitrogen pressure inside the loading cylinders which forces the piston to move downward; this pushes the brass bracket downward with the designed force. The two tension rods in each cell transfer the load to the loading cross bar, which applies axial static loading to the specimen through the thrust bearing, the load cell and the cap plate. This system achieved its objective of applying equal and simultaneous axial static load to both specimens and also without interaction with or interference from the torsional vibration system. Actual tests of two ice samples subjected to static load of 260 kN/m^2 for a period of 475 hours showed that the control of the static loading during the period of the test was satisfactory. The load was constant and equal on both specimens. The specimens were insured to be axially loaded during the test period by using a non-tilting device.

(iv) Dynamic loading system

Drnevich (1976) free-free torsional resonant column apparatus (Serial No.106) was modified and employed to apply vertical loads without influencing the free vibration characteristics of the

sample-apparatus system. A vertical cylinder of ice or frozen soil is subjected to steady-state sinusoidal vibration at its base with the other end free except for a light, relatively rigid cap. The input motion and output sample resonance are both observed and measured with piezoelectric transducers attached to the cap and base plates at the passive and active ends of the specimen.

Schematic diagrams illustrating the dynamic loading system as well as associated dynamic test equipment are shown in Fig.3.5.11. Electrical signals from the sine wave oscillator to the coils cause torsional vibration of the active beam. The dynamic creep triaxial cell is bolted to the active beam attachment plate. The torsional vibration of the active beam is transmitted to the base of the specimen (active end). The electrical connections consist mainly of two circuits, namely the power circuit and the transducer circuit. A spectrum analyzer (Model 3580 a - Hewlett Packard) has been used to determine the frequency spectrum before starting the test, and then a frequency near the sample resonant frequency is selected for the long-term test using the sine-wave oscillator. An X-Y oscilloscope, a phase meter, an ac-voltmeter with analog output, and strip chart recorders have been used to monitor the vibration response of the active and passive end transducers.

The dynamic characteristics of the system as a torsional vibration device have been checked and found to be acceptable. The frequency spectrum has been recorded during actual testing of an ice sample with the anti-freeze bath inside the triaxial cell chamber. The apparatus resonant frequency has been found to be 32.15 HZ and the sample resonant frequency 168.30 HZ. The range of the vibration frequency is from 0 to 1000 HZ.

(v) Test Procedure

After stabilization of the temperature, static load is applied simultaneously to both specimens until a quasi steady creep rate is achieved. Note that the steady creep rate should be the same for both specimens, since they are from the same type of ice and subject to the same static loading and temperature conditions. Upon reaching the steady creep rate, torsional vibration is also applied to one of the test specimens at a frequency near the specimen resonant frequency. The statically tested specimen continues to be subjected to static loading only.

3.5.6 Discussion

Dynamic testing of permafrost is, at present, in its infancy. Varying applications require testing over a wide range of frequencies. This necessitates the use of different apparatuses, sample preparation and testing procedures depending on end use requirements. Test standards will then probably have to be set for various frequency ranges, e.g. creep, low frequency (earthquake research), and high frequency (elastic properties).

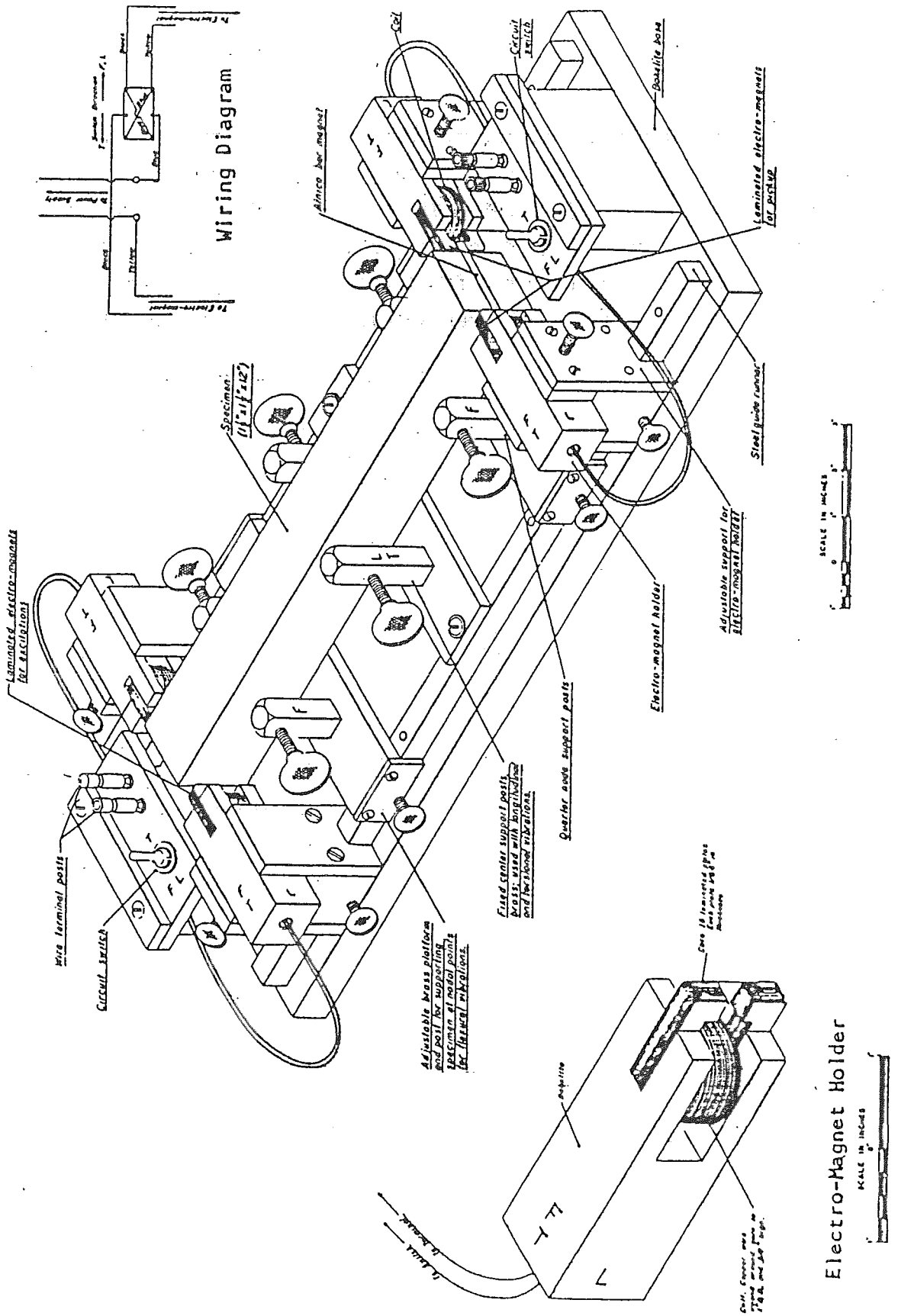


FIGURE 3.5.1 Electromagnetic Three-Mode Beam Vibrator (for flexural, longitudinal and torsional vibrations). (after Kaplar, 1969)

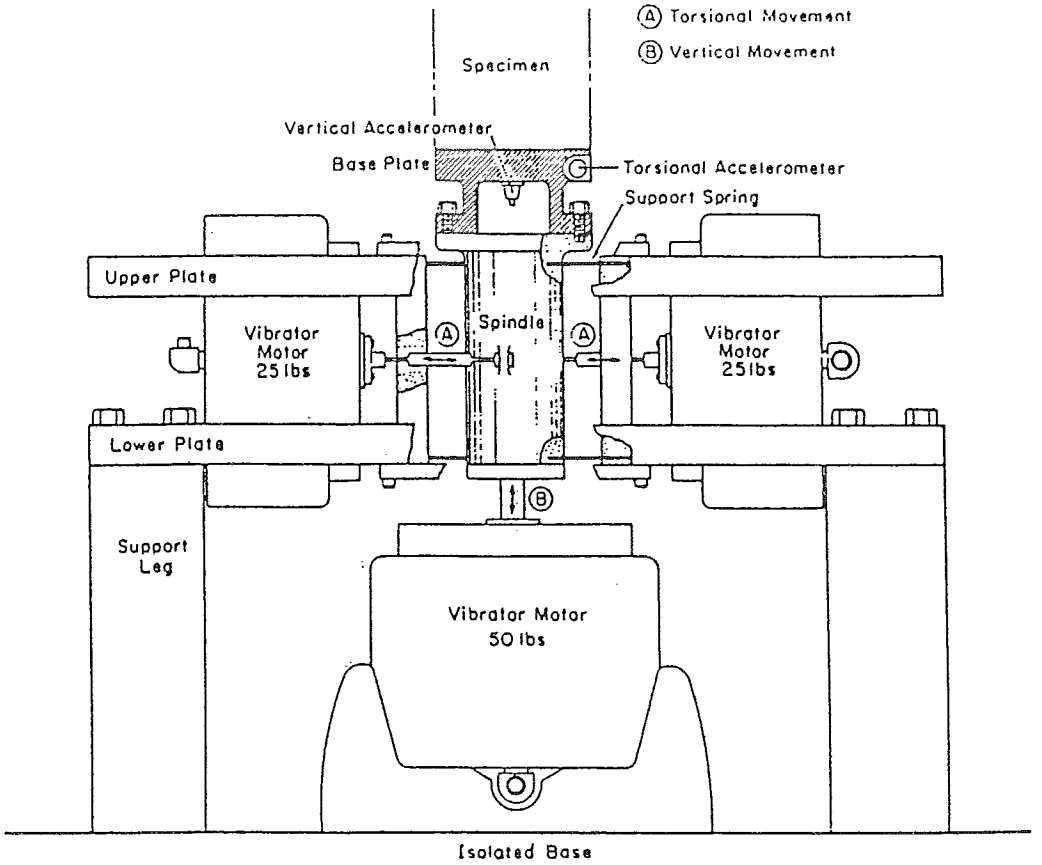


FIGURE 3.5.2 Schematic of Laboratory Test Apparatus. (after Stevens, 1973)

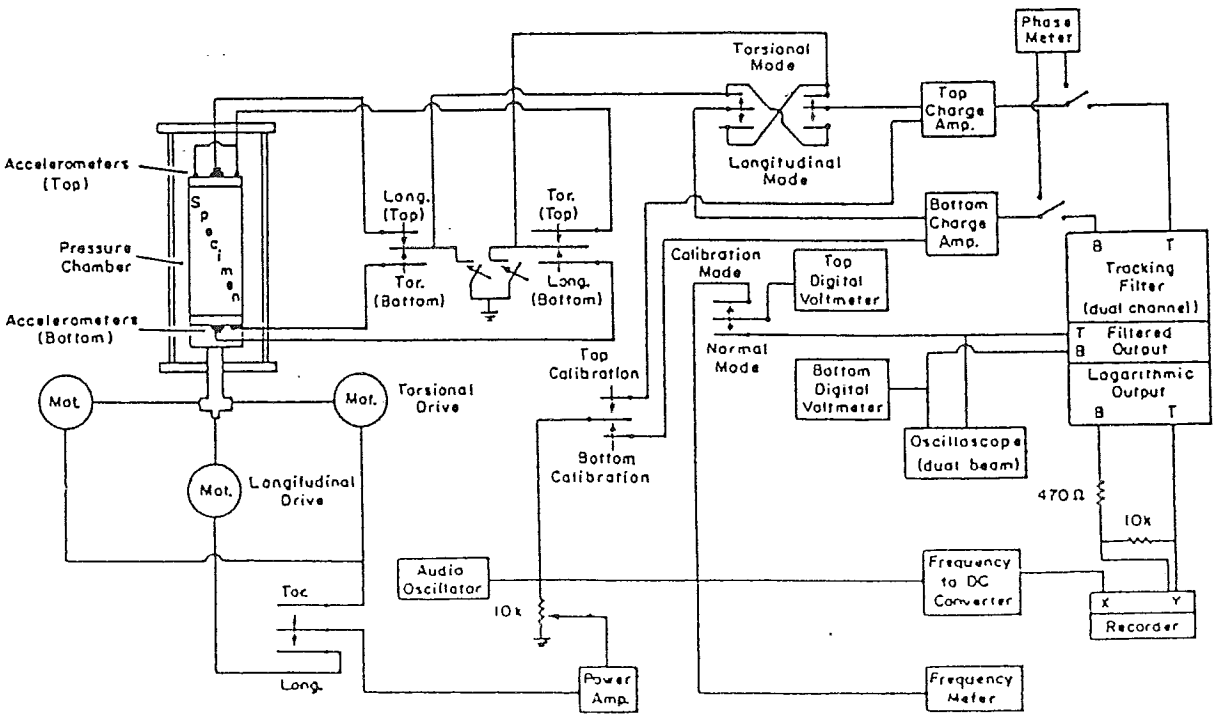


FIGURE 3.5.3 Schematic of Control and Readout System of Dynamic Test Apparatus. (after Stevens, 1973)

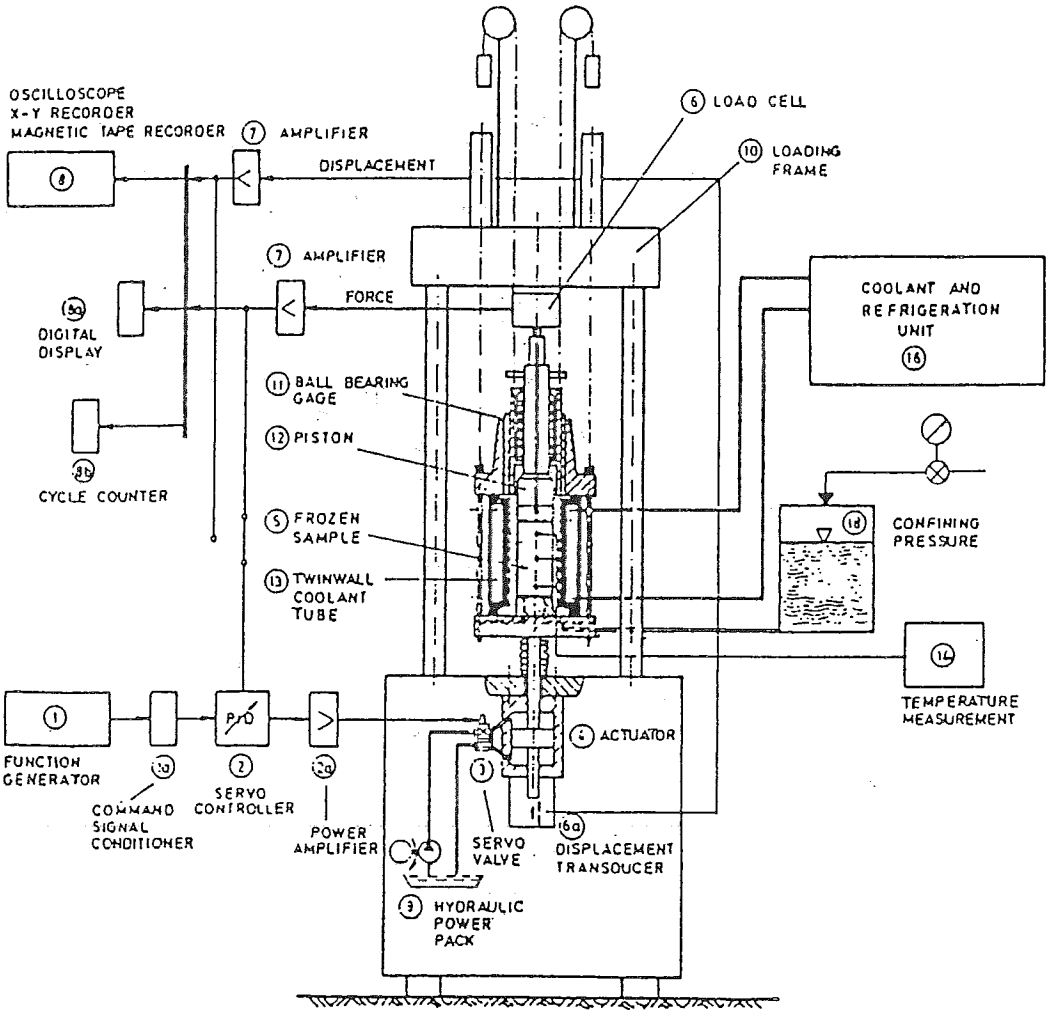


FIGURE 3.5.4 Dynamic Triaxial Shear Apparatus (TSW IIb) with Signal Flow Diagram. (after Jessberger and Jordan, 1982)

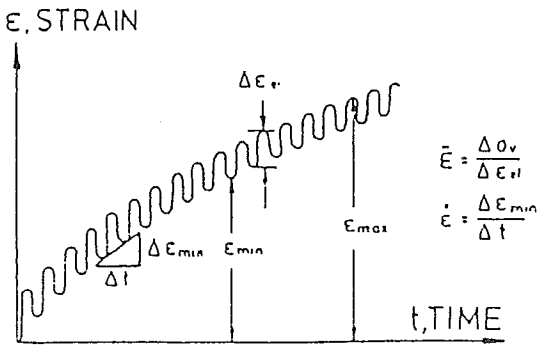


FIGURE 3.5.5 Typical Test Result of the Dynamic Triaxial Shear Test, Schematically. (after Jessberger and Jordan, 1982)

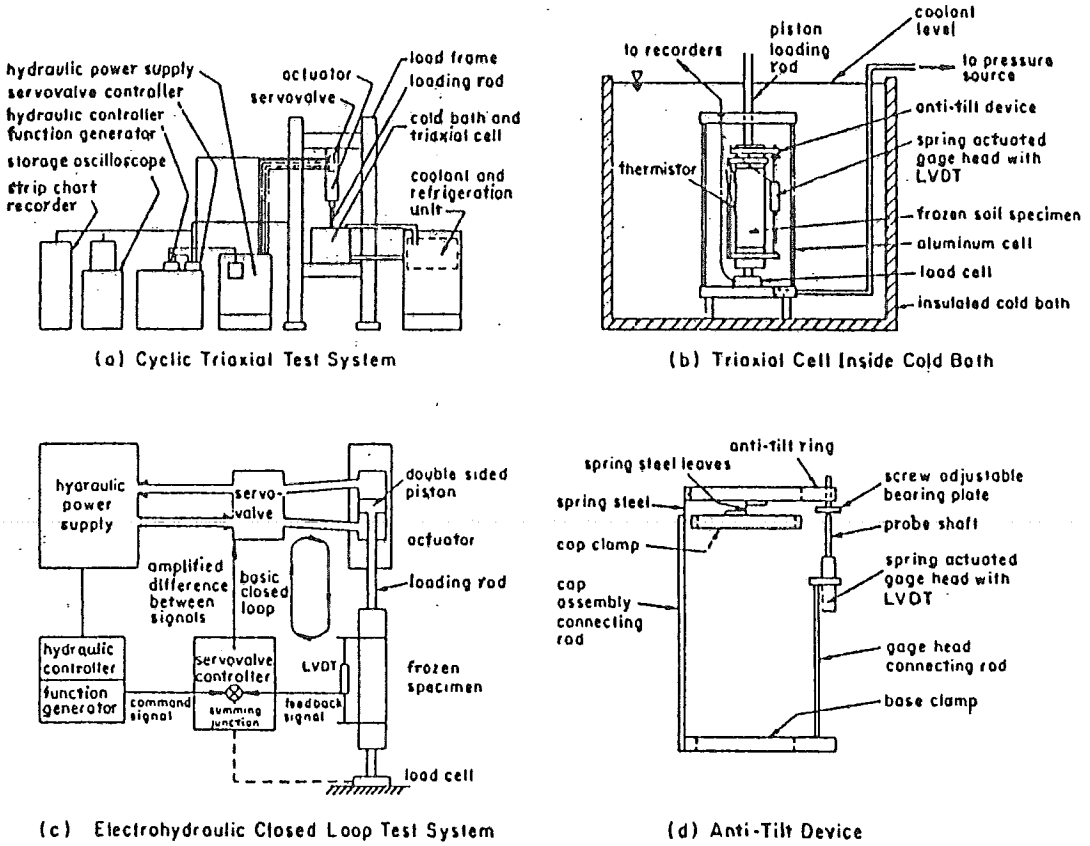
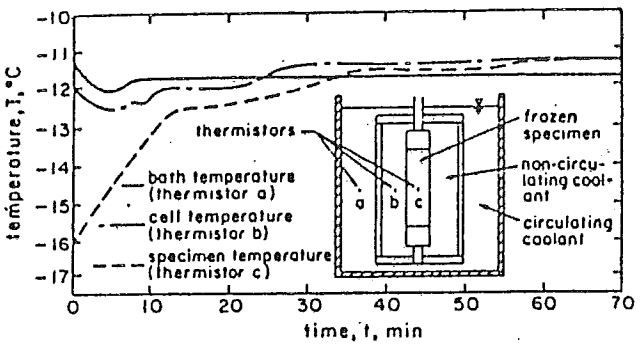
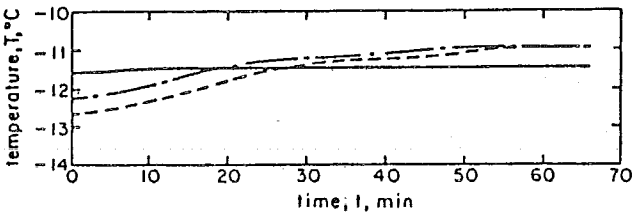


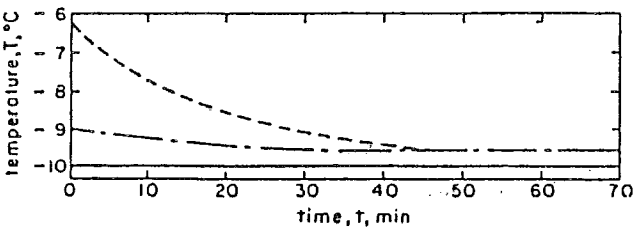
FIGURE 3.5.6 Schematic of Cyclic Triaxial System. (after Vinson, 1978)



(a) Variation of Temperature Using Steel Cap and Base - Ice



(b) Variation of Temperature Using Aluminum Cap and Base - Ice



(c) Variation of Temperature Using Steel Cap and Base - Clay

FIGURE 3.5.7 Specimen Temperature Versus Time for Different Test Conditions. (after Vinson, 1978)

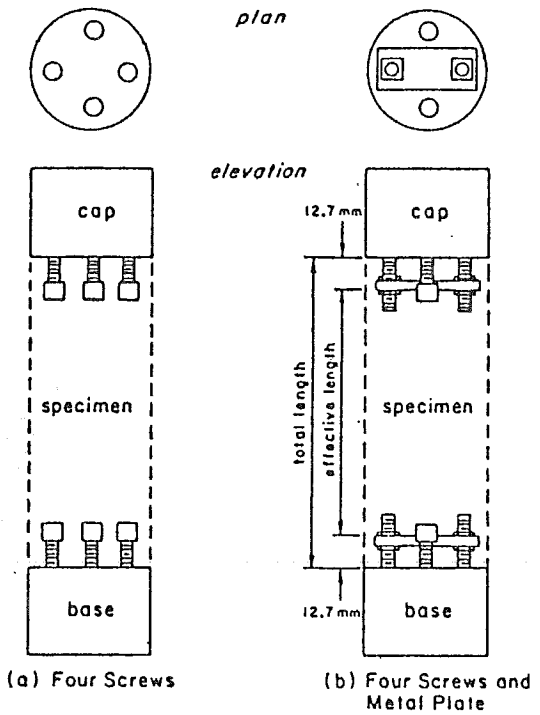


FIGURE 3.5.8 Coupling Devices Used in Cyclic Triaxial Testing (1 mm = 0.04 in.) (after Vinson, 1978)

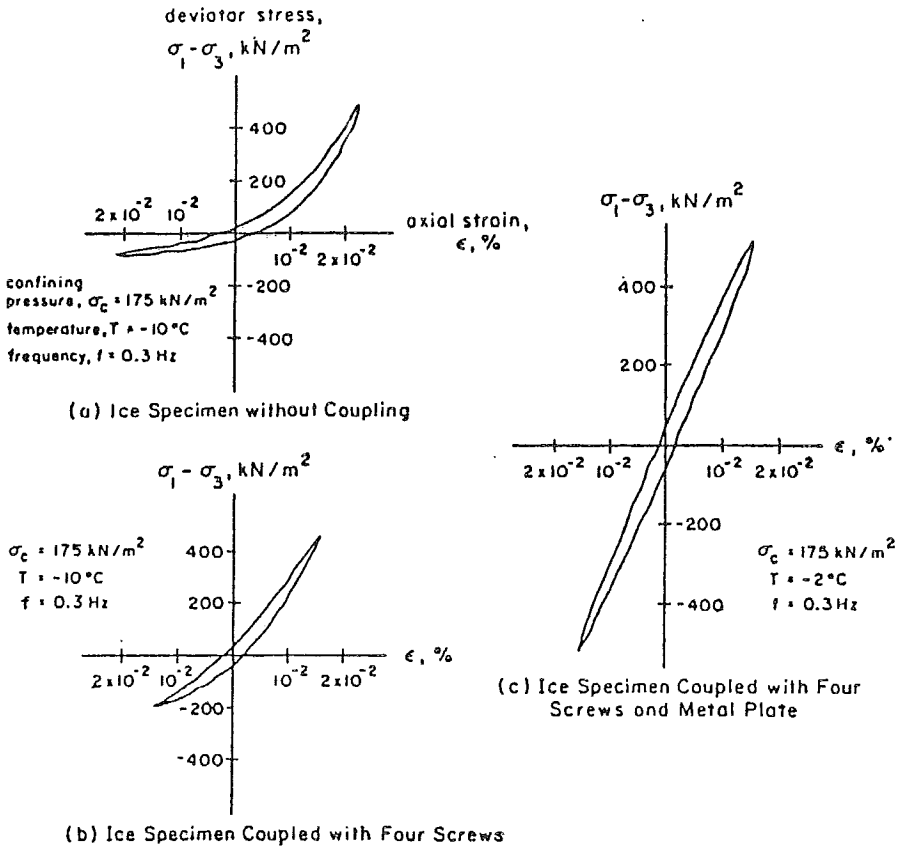
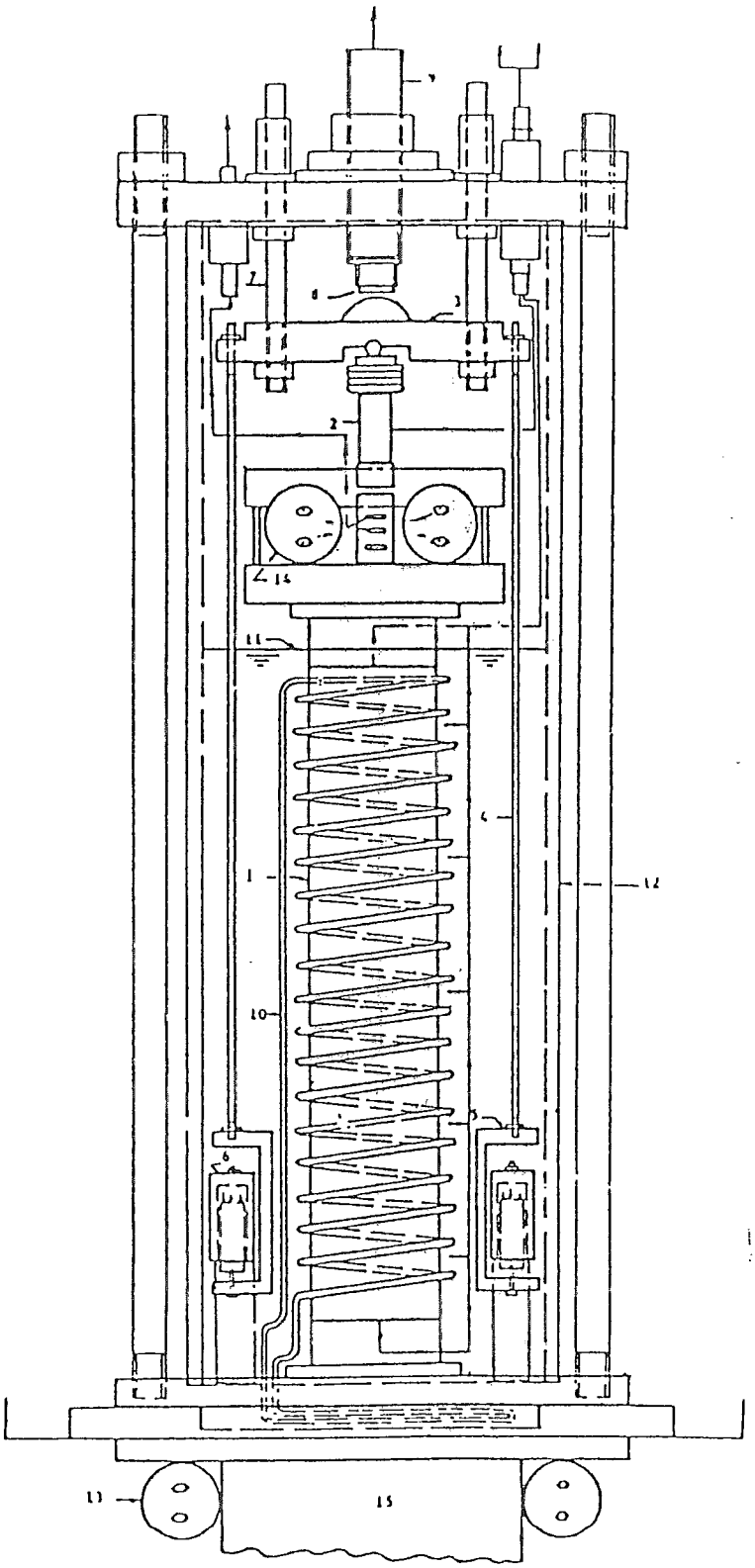


FIGURE 3.5.9 Typical Hysteresis Loops of Ice Specimens With Different Coupling Devices. (after Vinson, 1978)



Key to Fig. 3.5.10

1- Ice or frozen soil specimen.

2- Load cell and thrust bearing.

3- Loading bar to transfer the load from the two tension rods to the thrust bearing and then to the specimen. It has another two functions: firstly, mounting a displacement transducer target for measurement of vertical displacement and secondly as a holder of the two alignment bars for the non-tilting device.

4- Tension rods to transfer the load from the bracket(5) to the loading bar(3).

5- Static loading brass bracket to transfer the load from the piston to the tension rod (4).

6- Pressure cylinder and piston.

7- Two alignment rods to prevent tilting of the specimen. These two rods are fixed to the loading bar (3) penetrated the triaxial cell top plate, and adjust vertically by two pushings.

8- Kaman non-contacting vertical displacement transducer.

9- Displacement transducer threaded holder shaft.

10- Inner cooling coils.

11- Antifreeze bath (Cooling media).

12- Outer acrylic tube Chamber.

13- Active velocity transducers.

14- Passive velocity transducers.

15- Vibration Device.

FIGURE 3.5.10 Dynamic Creep Triaxial Cell. (after Youssef, et al, 1981)

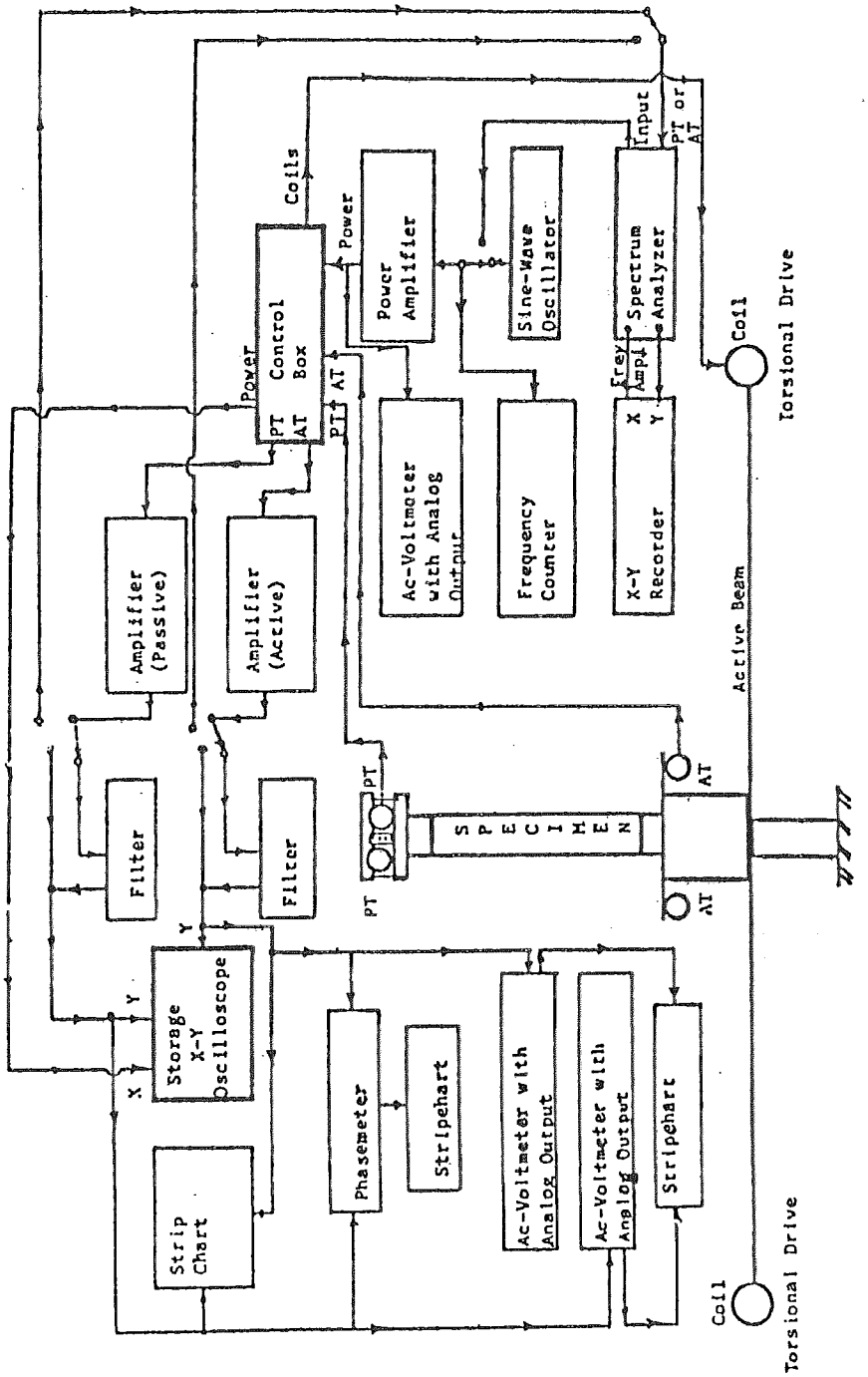


FIGURE 3.5.11 Schematic of Forced Vibration Dynamic Test Equipment. (after Youssef, et al, 1981)

3.6 THERMAL PROPERTIES

The position of the interface between thawed and frozen soil with respect to the ground surface for a given surface-temperature regime depends on the thermal properties of the strata located above and immediately below the interface. These thermal properties are important parameters in the determination of frost and thaw penetration and are indeed fundamental to all ground heat transfer problems. The basic thermal properties required for thermal analysis are thermal conductivity or thermal diffusivity, heat capacity, and latent heat. These vary with phase composition and hence temperature, soil type, water content, porosity, degree of saturation, density and organic content.

A. Judge, Earth Physics Branch of Energy, Mines, and Resources, however, expressed considerable doubt that the common use of Kersten's data is adequate for engineering design, (personal communication, 1982). He mentioned that Ontario Hydro is measuring its own thermal properties for the design of buried transmission lines.

Experimental apparatuses and procedures for the determination of thermal properties are given in the following sections.

3.6.1 Testing at C.R.R.E.L.

3.6.1.1 Development of Thermal Conductivity Probes (After Wechsler, 1966)

(i) Probe design

Based upon the review of the literature and the design calculations 18 laboratory-type probes were designed and constructed. A

number of different designs were prepared in order to investigate variables such as probe diameter, length to diameter ratio, probe construction material, type and location of temperature sensor, probe heat capacity and heater type. The general design of the probes was similar, i.e., a hollow protective sheath of metal or plastic was used to contain a heater and a temperature sensor. The void space within the sheath was filled with a plastic, ceramic or metal. Dimensions and other design data of laboratory probes are given by the authors.

(ii) Construction technique

A 'standard' construction technique was used in preparing most of the bifilar type probes. The sheath material was cut to the desired dimensions and the ends were made smooth. The heater wire (usually #38 or #40, nylon or Teflon coated constantan wire) was close wrapped in a bifilar manner (double wrap) on a stainless steel rod mandrel. The mandrel size was chosen so that when the heater wire was wrapped around it, the wire and mandrel would fit snugly into the sheath. The use of the bifilar wrap enabled both heater leads to be located at one end of the probe. The heater and mandrel were placed in the sheath, and the mandrel was carefully removed. The thermocouple, usually a #38 copper-constantan with nylon or Teflon coated wire, was placed in the hole left by the mandrel and positioned at the midpoint of the probe. Heavy coopper lead wires were normally soldered to the constantan heater wires at the top of the probes.

The void space in the probe was normally filled with an epoxy resin. The resin was a mixture of 10 parts Epon 828, 9 parts NMA, and a small amount of DMP 30. This resin cured effectively overnight at a temperature of about 70^{o}C. A hypodermic needle and syringe were used to fill the interior of the probe with the resin. After curing the resin and attaching the lead wires for the heater, the end of the probe was potted in Silastic rubber compound to protect the lead wires. The lead wires from the probe were connected to polarized connectors so that they could be rapidly connected and disconnected.

The probe using thermistors were constructed in a similar manner. The thermistors were type TX 1575 supplied by Victory Engineering

Corporation, Springfield, New Jersey. The thermisotr beads were attached to fine lead wires about 1 in. long. The lead wires were attached to #40 copper leads.

Probes which had the temperature sensors embedded in the wall required a slightly differeent technique. A small hole was drilled in the sheath and the thermocouple bead 'potted' in the wall with epoxy resin. The lead wires extended within the probe to the top as in other probes. Probes with ceramic inserts also required a slightly different, but not overly difficult, assembly technique.

Most of the probes were constructed without major difficulties. One was difficult to construct because of the shrinkage of the plastic outer tube during cure of the epoxy resin. The probe had to be prepared several times before an acceptable unit could be obtained. The probe was not very straight and required careful handling and emplacement.

The probes filled with Wood's metal also presented some construction problems. Wood's metal has a melting point below 200^{o}F. Initial attempts to construct metal-filled probes were not successful because of the corrosive action of the metal on the insulation of the heater wires, causing short circuiting between the heater wire, probe sheath, and thermocouple. By using a heater wire with a high temperature electrical insulation and by potting the thermocouple bead with a small droplet of epoxy resin before filling the probe with Wood's metal, the problem was eliminated. The Wood's metal was heated above the melting point, pulled into the probe under vacuum, allowed to cool and solidify, and the excess was trimmed off.

Several of the probes required simple repairs because of breakage of the thermocouple or heater wires at the top of the probe. Breakage was sometimes caused by flexing during use and insertion of the probe in the sample. Breakage of the lead wires was also attributed to the difference in thermal expansion of the wires and plastic filling and the temperature cycling betwen -40^{o} and +80^{o}F to which the probes were subjected.

(iii) Power supply and related instrumentation

A regulated D/C power supply (Electronics Measurements Company, Model 212A) was normally used to provide electric power for the probes. Prior to tests, the power supply was connected to a decade resistance box (General Radio Company, Type 1432-T) used as a dummy load to stabilize the power supply. A double pole-double throw switch was used to disconnect the dummy load and initiate heating. (See Figure 3.6.1 for instrumentaion diagram).

A Weston Model 911 milliameter and coltmeter (1/2% accuracy) were used to measure the current and voltage applied to the heater. A 12-storage battery was used to provide the higher currents required for several probes with low resistance.

(iv) Thermocouple probe instrumentation

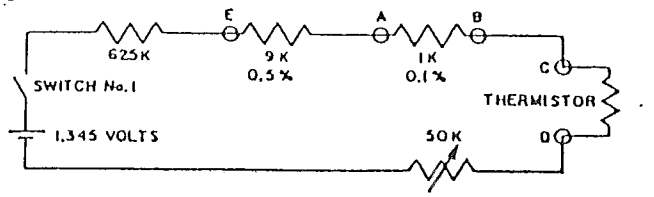
The instrumentation used for measuring the temperature indicated by the copper-constantan thermocouples in the probes consisted of a Leeds and Northrup Type K-3 potentiometer, with an Eppley Laboratory standard cell and 2-v storage battery, a Leeds and Northrup Type 2430-A galvanometer, and ice bath reference junction, and a Honeywell Electronic 19 recorder. The potentiometer and recorder were connected as indicated in Fig.3.6.1. In one position of the thermocouple switch the temperature indicated by the thermocouple could be read in a standard manner using the potentiometer and galvanometer. In the other position, the potentiometer was used to provide a bias voltage opposed to the thermocouple voltage. The difference between thermocouple output voltage and potentiometer bias voltage was indicated on the Honeywell recorder. The recorder was set at 100 microvolts full scale deflection so that an additional amplifier was not required. Full scale deflection (100 divisions) on the recorder corresponded to a temperature span of about $4^{o}F$.

The potentiometer-recorder combination described above was very stable and the output signals were usually free from extraneous noise. The thermocouple and heater wires were normally shielded by standard braided shielding to further reduce noise. Large transient currents in other apparatus in the laboratory occasionally produced small fluctuations in the recorder trace but did not otherwise influence the tests.

A single copper-constantan reference junction was used for all probes having this type of thermocouple. As described earlier, the thermocouple lead wires from the probes were attached to polarized plugs, which were attached to a mating connector containing the reference junction leads during a test. Because standard connectors (instead of copper-constantan thermocouple connectors) were used, a transient temperature change was observed on attaching a probe thermocouple plug to the reference junction connector. This transient was in the order of $0.5^{o}F$, and persisted for about 5 to 10 minutes until the temperature of both parts of the connector were equalized. The connectors were wrapped in fiberglass insulation to reduce convection effects and to aid in stabilization. The Chrome-constantan thermocouple contained a separate reference junction and no connector was required.

(v) Thermistor probe instrumentation

A different temperature measurement technique was required for the thermistor probes. A small power supply was designed and constructed to provide a known constant current of 2 microamperes through the thermistor. The power supply utilized mercury batteries, a 1000-ohm precision resistor across which the current could be measured, a 625 K and a 9 K resistor, and a variable 50 K ohm resistor to standardize the current despite the larger resistance change of the thermisotr with temperature. The circuit diagram is shown below:



Prior to a test, the voltage was turned on by switch #1, and the variable resistor was adjusted so that a voltage drop of 2 millivolts was measured with the K-3 potentiometer across the 1000 ohm resistor (terminals A and B). This standardized the current at 2 microamperes. The voltage across the thermistor could then be measured with the potentiometer across terminals C and D. The thermistor resistance could be determined from the current and voltage, and the temperature obtained from a resistance-temperature calibration curve. During a test, the voltage across the thermistor was measured with the potentiometer-recorder combination described above. Since the current in the thermistor was standardized, the voltage change was indicative of the resistance change and hence the temperature change. The resistance of the thermistors used in the probes vaied from about 20K ohm at $-40^{o}F$ to about 800 ohms at $90^{o}F$. The sensitivity of the potentiometer-recorder system varied with temperature; full scale recorder deflection corresponded to about 0.4 to $4^{o}F$ at temperature of 90^{o} and $-40^{o}F$, respectively. The power dissipated in the thermistor varied from about 3×10^{-9} to 80×10^{-9} watts. Because this power was negligible compared to that supplied by the probe heater wire, self-heating of the thermistor was not a problem.

(vi) Sensor calibrations

The copper-constantan thermocouples and the thermistors were calibrated to determine their temperature dependence. A recirculating water bath was used to provide a stable temperature from the ice point to about $100^{o}F$. Temperatures of the bath were measured with a Mueller bridge, a calibrated platinum resistance thermometer, and a calibrated mercury in glass thermometer. The accuracy indicated in the calibration certificates is better than $\pm 0.03^{o}C$, and usually about $\pm 0.01^{o}C$. Reading errors due to

parallax may introduce temperature measurement errors of about ±0.03°C. A thermometer inserted with the probes in a glass Dewar was used for temperatures from the ice point to about -40°F. The Dewar was filled with isopropyl alcohol and cooled with dry ice. The fluid was continuously mixed to provide temperature uniformity during calibration.

The output of the thermocouples was measured with a Leeds and Northrup Type K-3 potentiometer and Type 9834 Null detector. A reference junction was provided at the ice point by a Joseph Kaye automatic reference junction for copper-constantan thermocouples, and an ice bath was used for the Chromel-constantan thermocouple. The thermistors were calibrated using the power supply and instruments described previously for temperature measurement.

The outputs of all copper-constantan thermocouples differed from those given by the standard thermocouple tables by less than ±0.005 millivolts over the entire calibration range. Therefore, the standard tables could be used in converting thermocouple output to temperature for all calibrated and uncalibrated copper--constantan thermocouples.

The Chromel-constantan thermocouple has an output which is approximately 50% greater than a copper-constantan thermocouple over the temperature range used. A plot of temperature versus emf was prepared and used in reducing the experimental data.

A plot of logarithm of voltage across the thermisotr versus temperature was prepared. This plot was almost linear as could be expected from the normal behaviour of thermistors. Empirical equations were derived from segments of this plot to relate temperature to the voltage readings. These equations were used in reducing data for the thermistor probe.

(vii) Measurement procedure and technique

A standard measurement procedure was adopted for all test runs. Sample preparation and methods of probe emplacement varied throughout the program. When the probe was emplaced and sufficient time had elapsed so that the probe was close to temperature equilibrium with the sample, and the sample in equilibrium with the surroundings, the following procedure was carried out:

1) The probe thermocouple (or thermistor) and heater plug was attached to the connector leading to the power supply and potentiometer. Glass fiber wool was wrapped around the connector.

2) The potentiometer was standardized and the thermocouple output, suitably biased by the potentiometer, was recorded at a chart speed of 5 min/in to observe the temperature stability of the system.

3) The dummy resistor was set at a value corresponding to the resistance of the probe being used and power was applied to the dummy load at the desired level to stabilize the power supply.

4) After the sample had come to apparent temperature equilibrium (defined as temperature change of less than $\pm 0.1^{o}F$ over several minutes), the probe temperature was measured using the potentiometer and galvanometer.

5) The recorder was again placed in operation so that the potentiometer provided the required bias voltage and the potentiometer was adjusted to give zero reading on the chart. A chart speed of 1 min/in and highest amplification (100 microvolts full scale) were normally use.

6) If the chart reading was steady, the power was switched from the dummy lead to the probe heater. Readings of voltage and current were recorded in a data book and on the chart paper.

7) When the output of the thermocouple had increased by 100 microvolts, the potentiometer bias voltage was increased by 100 microvolts, thereby returning the recorder pen to the zero reading. This procedure was repeated as often as necessary.

8) The test was continued for about 20 minutes, with current and voltage readings made several times during this period.

9) At the conclusion of the test, the power was shut off and the probe system allowed to come to equilibrium again. Tests with the same probe were repeated (after at least 1 1/2 hours for establishment of equilibriuim) or another probe was tested.

The recorder, voltmeter, and ammeter were calibrated and checked periodically. The procedure described above was modified slightly when thermistor probes were used in order to make the desired temperature measurements.

Data from the tests were taken from the recorder chart paper and plotted in either of two ways: 1) the millivolt readings were converted to temperature rise above the initial temperature and plots were made of temperature rise versus logarithm time, (2) plots were made of voltage increase above the initial voltage versus logarithm time. Straight lines were drawn by inspection through the greatest linear data region. The thermal conducti-

vities were calculated from the slope of the line, the thermocouple emf-temperature relation, the voltage, current and probe length. For thermistor probes, output voltage data were reduced to temperature values by the empirical equations described previously before curves were plotted. Between 5 and 15 tests could be made per day of operation, depending upon the type of sample, the probe test schedule, and the temperature conditions used.

3.6.1.2 After Haynes et al (1980)

The authors performed a study to determine thermal diffusivity of frozen soil. Within this context specific heats were determined for 10 materials and thermal conductivities for Fairbanks silt, Ottawa sand and Hanover varved clay using the guarded hot plate method (ASTM C-177-71). Test apparatuses and procedures are described below.

A. Determination of Specific Heat

Specific heat determinations were made with a Perkin-Elmer differential scanning calorimeter, model DSC-1. We determined the specific heat values by measuring the power required to change the temperature of a test sample and a reference sample being scanned at the same time and at the same constant temperature rate. This difference in power was recorded on a strip chart recorder.

The calorimeter can scan at temperature rates from 0.625°C/min to 80°C/min. The higher the rate, the greater the differential power required, but fast rates reduce the resolution in determining the specific heat at any set temperature. The scanning rate for this study was 20°C/min.

In these tests, the cover for the sample holder was filled with liquid nitrogen to allow specific heat measurements to be made at temperatures below -50°C. When ambient humidity became a problem at the low temperatures, an enclosure with a continuously circulating nitrogen supply was erected over the sample holder of the calorimeter. This eliminated the moisture problem.

The specific heat samples weighed between 25 and 100 mg. The sample weights were determined by 0.1 mg. Only fine-grained soils, i.e. those passing the No.20 mesh (00.841 mm) sieve, could be tested with this calorimeter.

The sample containers were aluminum pans 0.635 cm in diameter and 0.254 cm deep with covers that could be placed in a container crimping apparatus and sealed to prevent loss of moisture during a test.

Once the samples had been placed in the containers, weighted, and sealed, they were put in the calorimeter test holder beside the reference sample. The liquid nitrogen cover pan was placed over the top of the container and the sample temperature was reduced and allowed to stabilize. Then the test sample and reference sample were changed to -50°C at a 20°C/min rate.

B. Determination of Thermal Conductivity

(i) Apparatus and Sample Preparation

Samples of three different soils (Fairbanks silt, Ottawa sand and Hanover varved clay), were prepared in the laboratory at varying moisture content. Details of the sample preparation are given by Haynes et al (1980). A schematic of the guarded hot plate apparatus is shown in Fig.3.6.2.

(ii) Procedure

The first samples tested were in acccordance with ASTM C-177-71 using the guarded hot-plate testing apparatus.

After testing the Fairbanks silt using two identical samples, the top sample was removed and replaced with a standard gum rubber sample. The tests were repeated and the results compared.

The remainder of the testing program was concluded using the standard gum rubber sample as the second sample.

3.6.1.3 Direct Measurement of Thermal Diffusivity (After Hoekstra et al, 1973)

The authors describe a method to determine the thermal diffusivity of a soil through the application of a sinusoidal temperature wave to the periphery of a cylindrical specimen. The thermal diffusivity is

obtained from the ratio of the amplitude and difference in phase of the temperature wave at the periphery and in the center.

(i) Apparatus

(a) General

In dealing with soils and rocks, cylindrical samples with diameters ranging from 7 to 15 cm are convenient both for packing and coring. Smaller samples are either difficult to constitute or can not adequately represent the large grain sizes in some soils and rocks.

With a sample 10 cm in diameter the optimum frequency range can be computed from equation 4 and 5. In Fig.3.6.3 the ratio of the amplitude of the temperature wave in the center and at the periphery is plotted as a function of frequency for a sample diameter of 10 cm. The different curves span the range of diffusivities that can be expected in soils and rocks. The optimum frequency range is clearly centered around 5×10^{-4} cps. A frequency of 2 cycles per hour (5.55×10^{-4} cps) was later used, because of equipment availability.

The equipment components are shown in Fig.3.6.4. The sample mold was maintained at a constant ambient temperature by circulating coolant from a constant temperature bath through an annular space in the sample holder. The temperature was varied from ambient through a heater attached to the inner aluminum wall of the sample holder. The sample mold was an aluminum cylinder that fitted snugly in the sample holder. The temperature was measured at the periphery by a resistance wafter attached to the aluminum mold and in the center by a thermistor in a metal probe. The temperature was recorded by a two-pen strip chart recorder.

(b) Function generator

The function generator was a sine wave potentiometer driven by a synchronous motor through a gear reducer. The gear reducer allowed a selection of frequencies, but a frequency of 5.5×10^{-4} cps (2 cycles per hour) was used throughout the experiments. This frequency was satisfactory for the range of thermal diffusivities (0.001 to 0.01 cm^2/sec) encountered in soils and rocks. The output of the sine wave potentiometer was varied around 1 volt rms.

(c) Programmable power supply

The circuitry of the programmable power supply is shown in Fig.3.6.5. The maximum power that can be controlled by this circuit is 100 watts, which was found sufficient in the tests. The power to the heater was regulated by controlling the firing angle of a Silicon Controlled Rectifier (SCR). The control circuit input consisted of a two-transistor differntial amplifier. One input to the amplifier was from the function generator, and the other was from a temperature sensor (feedback device). Since the feedback device was a temperature sensor on the sample wall, the voltage wave of the function generator was converted to a temperature wave at the sample wall.

(d) Temperature measuring system

The temperature sensor at the periphery of the sample mold was a resistance wafer, and that in the center was a thermistor inserted in 0.29 cm OD copper tubing. Within the time limits of the project it was not possible to obtain a custon-made resistance probe of the same temperature sensitivity as the resistance wafter at the periphery. Identical resistance probes in the center and at the periphery would simplify calculation of the data. The temperature sensors formed one arm of a resistance bridge. The unbalanced ouput of the resistance bridge was fed to a two-pen strip chart recorder. This method of temperature sensing has a precision of better than $\pm 0.005^{o}C$ for measuring differential temperatures. The system was calibrated after each run by replacing the temperature sensors in the bridge with a precision variable resistor.

(e) Constant temperature bath circulator

The constant temperature bath circulator was a Forma Scientific Model 2095. However, an external temperature controller and an additional stirrer were used to control the temperature to within $\pm 0.05^{o}C$.

(f) Sample holder and mold

Figure 3.6.6 is a machine drawing of the sample holder and mold. The Micro thermofoil heating films were fixed to the inner wall of the annular space of the sample holder with Scotch Adhesive No.467. Insulation was applied to the outside of the sample holder. The sample holder and mold were of simple, inexpensive construction and the design allowed much versatility in changing sample diameter and length.

3.6.2 Testing at N.R.C.,Canada

3.6.2.1 Thermal Conductivity Laboratory Studies

A. After Penner (1970) and Penner et al (1975)

(i) Discussion of methods

(a) Steady-state method

For the steady-state method a uniform temperature gradient is applied and the sample is allowed to condition thermally until constant heat-flow conditions are attained. Kersten (1944) used this method with a ΔT of $10^{o}F$ (5.6 ^{o}C) across a sample 4.25 in (10.8 cm) thick. Such conditions can induce thermally activated diffusion of water in both frozen and unfrozen unsaturated soils (Hutcheon, 1958). If the sample is of finite thickness, water or ice accumulates at the cold end and drying occurs at the warm end, but the extent to which this occurs depends on the duration and magnitude of the imposed temperature gradient, the nature of the soil, and the degree of saturation. The process is normally more unpredictable in the field than under precisely controlled laboratory conditions (Hutcheon,1958).

The ice-water ratio imposes further difficulties in thermal conductivity measurements since it is a function of temperature in fine-grained soils (Penner,1970). When samples are subjected to a temperature gradient (as in the steady-state method) the soil sample does not have a constant ice-water ratio throughout its length. Because the thermal conductivity of ice is more than four times greater than that for water, the thermal conductivity of the sample would also not be constant.

(b) Probe method

The use of the transient heat-flow method for determining thermal conductivities of unsaturated soils is also not without difficulties. The thermal probe or needle is the most common apparatus used in the transient heatflow technique. The problem of induced moisture flow in an unsaturated system is similar to the steady-state method but may be more critical as the temperature gradients next to the probe can be much greater than those that usually occur in the steady-state method. Woodside (1958) suggested that increasing the diameter of the probe and using low heat inputs would reduce the thermal gradients and thus decrease the induced moisture flow. Large diameter probes are usually not sufficiently long to satisfy the requirement of a

line heat source assumed for the development of the simple theory describing their behaviour.

(ii) Apparatus used

In recognition of the difficulties associated with the two main methods, particularly for unsaturated soils, the line heat source probe technique was considered the preferred method.(Fig.3.6.7) The temperature gradient in the vicinity of the probe was kept as small as possible by maintaining a low power input to the heater but consistent with the ability of the temperature measuring equipment to detect temperature changes in the probe with acceptable limits of accuracy. An advantage of the probe method, compared with the steady-state method, is that the thermal conductivity determination is of short duration. This is a time-saving feature which also reduces the time that the sample is subjected to thermal gradients - the cause of thermally activated diffusion. In general, the apparatus is less expensive than steady-state equipment and is simpler to operate.

The line heat source was a hollow probe, 21.27 cm long, with an outside diameter of 0.051 cm. It contains a uniformly spaced spiral heating coil with a nominal electrical resistance of about 1600 ohms. A constantan-chromel P thermocouple is located inside the spiral heater halfway along the probe. Some of the probe thermocouples were calibrated by the Division of Physics, National Research Council of Canada. Probes acquired more recently were calibrated by comparing them at several temperatures with those previously calibrated. A further calibration check was made later in the study using a calibrated platinum resistance thermometer and a G2 Mueller bridge with a temperature measuring capability of $\pm 0.001^{o}C$.

Power to the probe was supplied with an electronically controlled constant current source. Current constancy was checked by continuously monitoring the voltage across the heater terminals. The voltage output of the probe thermocouple, referenced to an ice bath, was measured at 20 to 30 s intervals with a multipoint data acquisition system. The signal was preamplified by a factor of 100 to obtain greater precision in voltage measurements.

The level of power supplied to the probe heater depended on the thermal conductivity of the soil. For low thermal conductivity samples it was as low as 0.72 W/m^3, for high conductivities it was never greater than about 1.7 W/m^3. The power supply had to be maintained at a level sufficiently high to give temperature changes that could be measured with reasonable precision and accuracy. A probe temperature change of about $0.06^{o}C$ during the conductivity determination was considered to be the lowest acceptable for satisfactory accuracy. Later in the study an

improved signal amplifier was acquired that permitted the temperature rise of the probe to be reduced to 0.024 degrees.

Conductivity was calculated from the temperature rise of the probe using the following equation:

$$k = \frac{Q}{4\pi\Delta T}(\ell_n t_2/t_1) = \frac{Q}{4\pi} \text{ slope}$$

where t_2 and t_1 are the times corresponding to the probe temperature change ΔT and Q is the power input. Plotting the change in temperature against the logarithm of the time gives a straight-line relationship. The initial temperature rise in the period from 0 to 2 min was not used in the thermal conductivity calculation because the ln time temperature plot is not linear immediately after the power is turned on.

The computer was used to determine the least squares fit to the ln t versus temperature measurement, the standard error (S.E.) of measurement, the probe temperatures from the e.m.f. - temperature equations, and the thermal conductivity, k. Pertinent information such as current, power supply per unit length of probe, and standard error in the slope of the linear fit to the measurements are given in tabular form along with the thermal conductivity results.

(iii) Procedure

(a) General

The thermal conductivity for each of the 10 soils was determined with apparatus shown in Fig.3.6.8 at three moisture content/density conditions. Samples for the conductivity measurements were prepared in molds using the same compactive effort per unit area of the container and the same soil layer thickness as in the standard Proctor procedure. The sample molds were PVC pipes 12 inches (30.48 cm) high and 5.7 inches (14.48 cm) in diameter with a 0.5 inch (1.27 cm) wall thickness. The diameter of the mold was shown (by calculation) to be large enough so that no temperature rise was experienced at the outer edge of the sample during the 15 min thermal conductivity determination.

To facilitate insertion of the thermal conductivity probe after the samples had been prepared, a stainless steel wire was tightly held along the center line of the mold between a clamp at the bottom and a rotatable brass yoke at the top during sample preparation. The yoke was rotated between successive blows during compaction to ensure a uniform density throughout the sample. The sample was built up in layers in this way until it

was higher than the length of the thermal conductivity probe. A layer of molten petroleum wax was poured on top of the sample to prevent moisture loss. As indicated earlier, three samples of different density and moisture content were prepared in this way for all soils.

(b) Probe Insertion

The thermal probes were coated with a silicon grease and inserted into the sample from the top as the stainless steel wire was withdrawn from the bottom of the mold (Fig.3.6.8). The hole in the bottom was sealed with wax or grease after the wire had been removed. After waxing the plastic terminal block to fix it in position, the sample and assembly were placed in a constant temperature chamber for conditioning.

(c) Sample Conditioning

All three samples of each soil, after preparation in the molds, were placed in the constant temperature chamber and conditioned to a preselected temperature. The samples were insulated at both ends so that thermal conditioning would be attained by radial heat flow. The chamber temperature variation was within $\pm 0.03^{o}C$ but the variation inside the specimen was less because of the thermal lag caused by the mold wall.

Thermal conductivities were measured at three nominal temperatures: 5, -5, and $-15^{o}C$. It required 24 to 36 hours to bring the samples from room temperature to $+5^{o}C$, about 48 hours from 5 to $-5^{o}C$, and a further 24 to 36 hours from -5 to $-15^{o}C$. The longer period between 5 and $-5^{o}C$ was due to the latent heat release during the freezing process.

(d) Density and Moisture Content

The moisture content of each of the samples was determined during preparation by sampling the bagged soil in two or three different places. The wet density was determined from the volume of soil in the mold and the weight of the wet sample after the thermal conductivity runs had been completed.

B. After Slusarchuk and Foulger (1973), Slusarchuk and Watson (1975)

A thermal conductivity probe apparatus was designed and built by Slusarchuk and Foulger (1973). Tests on fine grained ice rich permafrost soils from Inuvik, Northwest Territories, are described by

Slusarchuk and Watson (1975). The equipment design and test procedures are given below.

(i) Apparatus

(a) General

The cylindrical probe consists of an outside stainless steel shell surrounding a heater coil wound on an acrylic plastic tube. The heater coil consists of teflon coated constantan wire. The void space around the heater coil between the plastic and stainless steel tubes is filled with a high thermal conductivity epoxy. A bead type thermistor is potted in the wall of the plastic tube with the same epoxy. The electrical leads from the thermistor are led up the probe inside the plastic tube. The void space inside the plastic tube is filled with a casting resin. A schematic drawing of the probe is shown in Fig.3.6.9.

Fabrication of the probe commenced with the polishing of a 15 inch length of stainless steel tubing. A stainless steel plug is made to screw into the bottom of the tube to a depth of 1/4 inch. A hole is drilled in the wall of a 15 inch length of plastic tubing approximately 6 1/2 inches from the bottom and a thermistor potted in the hole with epoxy. Another thermistor is generally positioned about 2 inches above the main thermistor. This assembly is placed in an oven at 70°C for several hours to cure the epoxy. Constantan wire is then wound tightly in a bifilar manner around the plastic tube to form the heater. This procedure may be simplified if a lathe is available that can be adjusted to rotate slowly. At this stage the leads of the thermistors and heater coil are inside the plastic tube and protrude from the top. The void space inside the tube is filled with a casting resin cured at room temperature for 24 hours. With the plug removed the inside of the stainless steel shell is swabbed with epoxy and a coating of it built up over the heater coil and plastic tube. While rotating slightly, this is inserted into the stainless steel tube. The plug is then screwed into the shell, forcing the heater assembly back. The probe is cured overnight at 70°C. Finally, the heater and thermistor leads are soldered to a miniature nine-pin connector which forms the head of the probe.

(b) Bridge and Heater Construction

The basic bridge circuit is a Wheatstone bridge utilizing four precision 10,000 ohm resistors, a precision 12,000 ohm decade box and a direct current null detector with a sensitivity of greater than 1 microvolt per division. The bridge is used to measure the resistance (and hence the temperature) of the thermistor in the probe. Resistances of up to 45,000 ohms can be measured with an accuracy of ± 1 ohm at room temperature under

laboratory conditions or an accuracy of ±2 ohms in a cold environment. For the thermistors used this means that temperatures can be measured with an accuracy of about ±0.003°C. A schematic drawing of the front panel of the bridge and heater unit is shown in Figure 3.6.9.

Power for the heater is supplied by a voltage regulator circuit utilizing an integrated circuit to drive a power transistor. During a test the voltage across the heater was virtually constant, varying by only ±0.02 per cent. Some long-term drift of the voltage was observed amounting to a change of 1.4 per cent over a 6-month period. This problem is easily overcome by taking a voltage reading once a week. Change in the resistance of the heater was about 0.01 per cent during a test. Because the resistance and voltage remained constant, so also did the power output of the heater.

Small batteries were used to power the heater, the Wheatstone bridge, and the galvanometer, and to be sure that these batteries were operating properly in the field, a series of voltage checks was built into the system. The bridge and heater batteries were checked with the galvanometer, using switch C (Fig.3.6.10), and the galvanometer batteries were checked using switch W.

(c) Thermistors

Bead type thermistors (Fenwal GB35J1) with a nominal resistance of 5000 ohms at room temperature were used. This resistance rose to about 35,000 ohms at -20°C. To obtain the accuracy required in the temperature measuremnts it was necessary to calibrate each thermistor. Prior to calibration the thermistors were cycled a number of times between boiling water and dry ice-alcohol baths. The thermistors were calibrated against a platinum resistance thermometer over a range of -20 to +35°C in increments of 5 °C at the Division of Physics, National Research Council of Canada. To obtain a temperature-resistance relation calibration data were used to determine the constants in the equation

$$\frac{1}{T} = A + B \ln R + C (\ln R)^3$$

where T = temperature, Kelvin
R = resistance, ohms
A,B,C = constants

This equation was used to generate a resistance-temperature conversion table for each thermistor. By this procedure temperatures could be determined to an accuracy of ±-.003°C.

Heat was generated in the thermistor when its resistance was being measured, but the amount produced, even in continuous operation, was kept low by using a very small current for measurement. The ratio of the heat produced by the probe over 1 cm of its length to that of the thermistor was approximately 10,000/1 so that the heat from the thermistor could be neglected.

(d) Calibration

The guarded hot plate is the standard method recommended for determining the thermal conductivity of a material (ASTM C177-63). Because of the inherent advantages of determining thermal conductivity of permafrost with a probe, it was selected as the test apparatus, but it was calibrated using the standard guarded hot plate method.

(ii) Test Procedure

A sample required approximately 24 to 28 hours to re-establish its original, constant temperature after a hole had been drilled in it. After this time it was moved to the test area of the cold room and placed on a 2 inch (5.08 cm) thick slab of styrofoam insulation. The stainless steel plug was removed and a probe with a surface layer of silicone grease was inserted into the hole. The probe had to be eased into the hole with a clamp attachment because of the tight fit. The clamp was secured to the top of the steel tube portion of the probe and was removed after insertion. The depth of placement of the probe was recorded. Two layers of glass fibre insulation 1 inch (2.54 cm) thick were wrapped around the sample and a 2 inch (5.08 cm) styrofoam slab placed on top. This slab had a hole in it sufficiently large to permit the electrical leads from the control unit to be attached to the probe.

The temperature of the sample was monitored before a test began. If the temperatures recorded over a 1/2 hour period did not drift more than $\pm 0.005^{\circ}C$, then measurement started. Temperatures were also monitored at the interface of the permafrost and insulation and at the outside surface of the insulation. All measurements were taken at approximately mid-height of the samples.

A measurement began when the heater coil in the probe was turned on (time zero). Temperatures were recorded at various times over a period of 30 to 60 min. The voltage and resistance of the heater were recorded at intervals so that the power input could be calculated. The time-temperature data were plotted on semi-logarithmic graph paper (time on the logarithm scale) and thermal

conductivity was determined from the slope of the straight line portion of the curve. In some cases temperatures were monitored after the measurement had been completed (i.e. after current to the heater had been cut off) to obtain a cooling curve. The samples had to cool for a period of approximately 24 hours before the temperature returned to its original, constant value and another measurement could be made. At least two measurements were made on each sample.

3.6.2.2 Apparent Specific Heat Laboratory Studies

A. Testing at National Research Council, Canada, After P.J. Williams (1964)

The freezing point of water is dependent on the chemistry of the water and on the other properties of the porous medium. As ice forms, the freezing point of the remaining unfrozen water decreases further below $0^{o}C$. Latent heat of fusion is thus involved in temperature changes to several degrees below $0^{o}C$. The latent heat and specific heat together constitute an apparent specific heat. Williams used a calorimeter to measure the apparent specific heat of several soils. The apparatus and general procedures are described below:

A calorimeter has been constructed (Fig.3.6.11) that permits measurement of the amount of heat added to or removed from a specimen to raise or lower its temperature by a certain amount. During warming of a sample, the only source of heat is that supplied at a measured rate by a heating coil attached to the specimen holder. During cooling, heat is lost from the sample holder at a practically constant rate determined by the temperature of the outer container which, in this case, is maintained lower than that of the sample holder by a certain amount.

Data from each thermocouple are recorded by a Speedomax recorder with preamplifier, at intervals of 5 minutes or less. Also recorded at 3-minute intervals on the same apparatus are temperatures from thermocouples placed on the inner side of the outer container (Fig. 3.6.11). Under normal conditions these latter readings serve merely to check the operation of the calorimetric equipment. The calorimeter is immersed in a tank of ethylene glycol solution, cooled by a compressor. During warming tests, when the only source of heat is to be the measured quantity supplied through the heating coil, heat exchange between the sample holder and its surroundings is avoided by maintaining the outer container at substantially the same temperature as the surface of

the sample holder. This is achieved by regulation of the temperature of the ethylene glycol in which the calorimeter is immersed. The temperature of the ethylene glycol normally tends to fall slowly. When its temperature and hence that of the outer container falls about 0.1°C below that of the sample holder, a blade heater in the glycol is automatically switched on until the temperature of the outer container is about 0.1°C warmer. The switching mechanism is operated by the amplified signal received from two thermocouples in series, on the sample holder and outer container.

During cooling (freezing), when heat is extracted at a nearly constant rate, the temperature of the outer container is maintained consistently lower than that of the sample holder. This is achieved by adjustment of the zero control of the amplifier, such that its output is sufficient to actuate the relay mechanism and heater only when the ethylene glycol becomes cooler than the sample holder by more than the predetermined amount.

3.6.3 Testing by Continental Oil Co.(After Wolfe and Thieme,1964)

The authors studied the physical and thermal properties of frozen soil and ice. Their apparatus and test procedures for specific heat and thermal conductivity measurements are described below.

A. Specific Heat

Specific heat determinations were made at several temperatures from +12°C to -180°C. The warmer determinations (+12, -7 and -24°C) were made by measuring the temperature rise in 50 ml of cold acetone when 1 gm of warm sample at a known temperature was added to the acetone. At these temperatures, the specific heat of a material of known specific heat (usually aluminum) was measured. Dry clay and silt were tested, and then their specific heat was calculated from the aluminum data.

The temperature was measured with a platinum resistance thermometer and a Mueller bridge. It was also recorded on a Speedomax recorder.

Specific heat values at -86, -132 and -180°C were obtained by measuring the amount of nitrogen gas evolved when a warm sample was introduced into a Dewar of liquid nitrogen.

The specific heat value obtained by either method is the average specific heat between the initial and final temperature of the sample.

Figure 3.6.12 is a schematic drawing of the equipment used for the lower temperature specific heat measurements. This figure shows the sample introduction system plus the liquid nitrogen and a waterfilled dropping funnel. The dropping funnel was used to measure the volume of nitrogen that evaporated when the sample was added to the liquid nitrogen. The sample was placed in the large modified stopcock at the upper left of Fig.3.6.12. It was dropped into the liquid nitrogen by turning the stopcock.

B. Thermal Conductivity

(i) Equipment

The thermal conductivities of clay, silt and ice were measured with equipment which was an adaptation of the guard-ring heater method. The sample was placed between a constant temperature liquid and an electrical heater of measurable output. The thermal conductivity was calculated from the temperature gradient across the sample and the amount of energy flowing through it at steady-state conditions.

The conductivity cell and heaters are shown in Fig.3.6.13. The heater consists of three 6 inch long units separated by synthane spacers. The center heater, which supplied heat to the critical portion of the samples, was connected to a Sorenson-regulated DC power supply. The end heaters, which insulated the center heater, were fed with AC and regulated with powerstats. The outer cavity contained the cold liquid. The heaters were centered in the inner cylinder by a packer. The space between the heaters and the cold chamber was filled with sample.

As is shown in Fig.3.6.13, the samples were about 1.3 inches thick and 16 inches long. They surrounded a 2 3/8 inch diameter heater. Thermocouples were placed at the warm and cool edges of the sample.

(ii) Procedure

Clay and silt were tested dry and at various water contents. Ice which was carefully frozen in place was also tested.

The outer jack coolants were: +7°C water; -30 and -40°C acetone; -78°C dry ice and acetone; -161°C liquid natural gas; and -195°C liquid nitrogen.

Once the thermocouples indicated the sample was at uniform temperature, the heater current was turned on. The powerstats were adjusted until the thermocouples showed the heaters were at equal temperatures After thermal equilibrium had been achieved, the temperature across the sample was measured. Thermal conductivity values were calculated from the equation:

$$K = \frac{QL}{\Delta T A_m}$$

where, K = thermal conductivity
Q = steady-state rate of heat flow
L = length of conduction path
ΔT = temperature difference
A_m = area through which heat flows at right angles

3.6.4 Testing at the University of Saskatchewan (After M.S.King,1978)

The author reports on thermal conductivity measurements of rock and soil at permafrost temperatures using a divided-bar apparatus. The apparatus and test procedure are given below:

(i) Divided-bar Thermal Conductivity Apparatus

The divided-bar thermal conductivity apparatus is shown in cross section in Fig.3.6.14. It consists of a loading frame with which the axial stress on a cylindrical specimen of rock and soil can be maintained constant. The divided bar is 3.81 cm in diameter and consists, from top to bottom, of a perspex loading cylinder, a brass heater element, a fused silica reference disc, a brass distance piece, the rock or soil cylindrical specimen, and finally, a second brass distance piece. The reason for placing the heater element above the specimen is to reduce the possibility of convective heat transfer in fluid-saturated porous specimens.

The apparatus has been calibrated with standard fused silica (GE 101) discs of four thicknesses. A thin film of DC 200 silicone fluid was used as a coupling medium between the faces of the fused silica standards and the brass discs in contact with them. A constant axial stress of 0.7 MPa was applied to the divided bar in each case. The power dissipated in the heater was held constant at 0.35 W during the calibration tests.

(ii) Procedure

The specimen was assembled in position in the divided bar, which was maintained at -10°C using thin film of DC200 silicone fluid as a coupling medium between the specimen and the brass distance pieces. It was then wrapped with a double layer of thin polythene film (Saran Wrap), so that the latter overlapped the two adjoining brass distance pieces. In this way, errors due to evaporation or sublimation of the specimen moisture were avoided. The assembled divided bar and loading frame were transferred to the test chamber, which was also maintained at -10°C. The desired axial stress of 0.7 MPa was then applied to the loading frame.

The temperature in the test chamber was reduced to -15°C and 1 day was allowed for the divided bar (with the heater turned off) to come to thermal equilibrium with its surroundings. The thermistor resistances were then checked to ensure no drift had occurred. The heater was turned on, usually with the power dissipation controlled at 0.35 W. Experiments have shown that a minimum time of 8 hours is required for the divided bar to come to thermal equilibrium when the heater is turned on or when the chamber temperature is altered.

The thermistor resistances were measured in the bridge at the lowest chamber temperature and the temperature drops across the fused silica reference and rock specimen were calculated. The temperature in the test chamber was then raised in the desired steps, allowing the divided bar 1 day to attain thermal equilibrium at each temperature step. After the completion of two sets of measurements at temperatures in excess of 0°C the chamber temperature was reduced to -10°C and the temperature drops measured after a day at this temperature. The heater element was turned off and, after thermal equilibrium in the divided bar had been attained, the thermistor readings were checked for drift.

3.6.5 Testing in Japan (After Katayama et al, 1973)

The authors describe a method for simultaneously measuring thermal conductivity, heat capacity and thermal diffusivity of wet porous materials in both the frozen and non-frozen states. Their test apparatus is described below.

(i) Apparatus

Figure 3.6.15 is a schematic of the measuring apparatus. In our experiment with wet sand, the specimen, having a dimension of 10 x 120 x 120 mm, was sandwiched by the standard specimen (reference material) composed of glass plates measuring 10 x 120 x 120 mm, with five on one side and six on the other (Fig.3.6.15).

Soda glass plates were chosen as the reference material and their surfaces were finished flat and smooth and greased to minimize thermal resistance on the contact surfaces. Thermal properties of the glass as measured by the authors' 'absolute method of transient heating' were established as follows:

$$K_{glass} = 1.03 \times 10^{-3} + 0.93 \text{ Kcal/mh C}$$

$$(cp)_{glass} = 1.22 + 538 \text{ Kcal/m}^3 \text{ C}$$

Copper constantan thermocouples of 0.1 mm diameter, used to measure the temperature of specimens, were bonded with adhesive to the heater surface and to the surface of the glass plate in contact with the specimen. An electrical heater made of 0.03 mm nichrome foil was sandwiched between the specimen and the glass plate. The specimen, glass plates and nichrome heater were bolted together as shown in Fig. 3.6.15 to ensure close surface contact.

The apparatus was kept in a constant temperature bath to maintain the specimen at a uniform initial temperature. By controlling the temperature of the bath, desired temperature can be readily obtained without a change in filling conditions.

Measurements were started after temperature distribution within the specimen was confirmed to be uniform. The nichrome foil heater was energized by direct current and the quantity of heat released from the heater calculated by measuring the current and voltage.

Temperatures were measured with C-C thermocouples at both surfaces of the specimen (Fig.3.6.16), and temperature responses were recorded with potentiometers, DC-amplifier and a pen recorder.

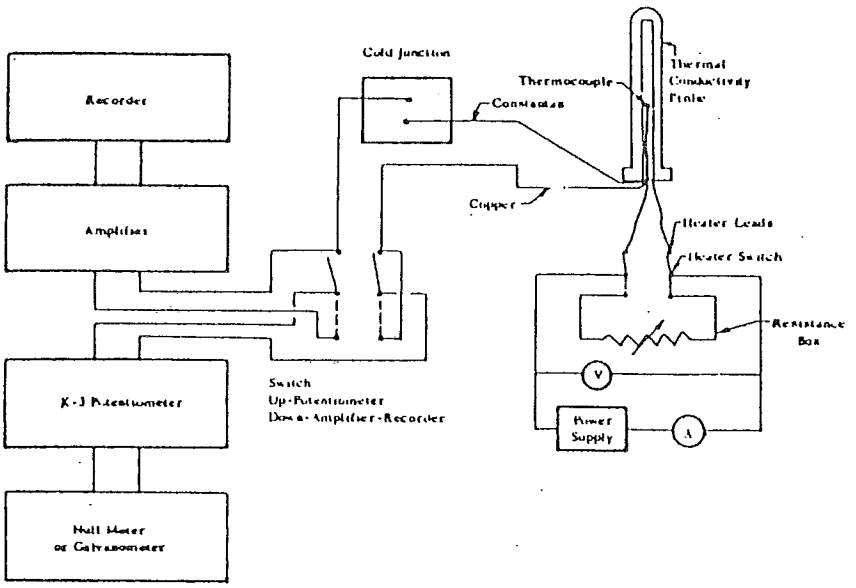
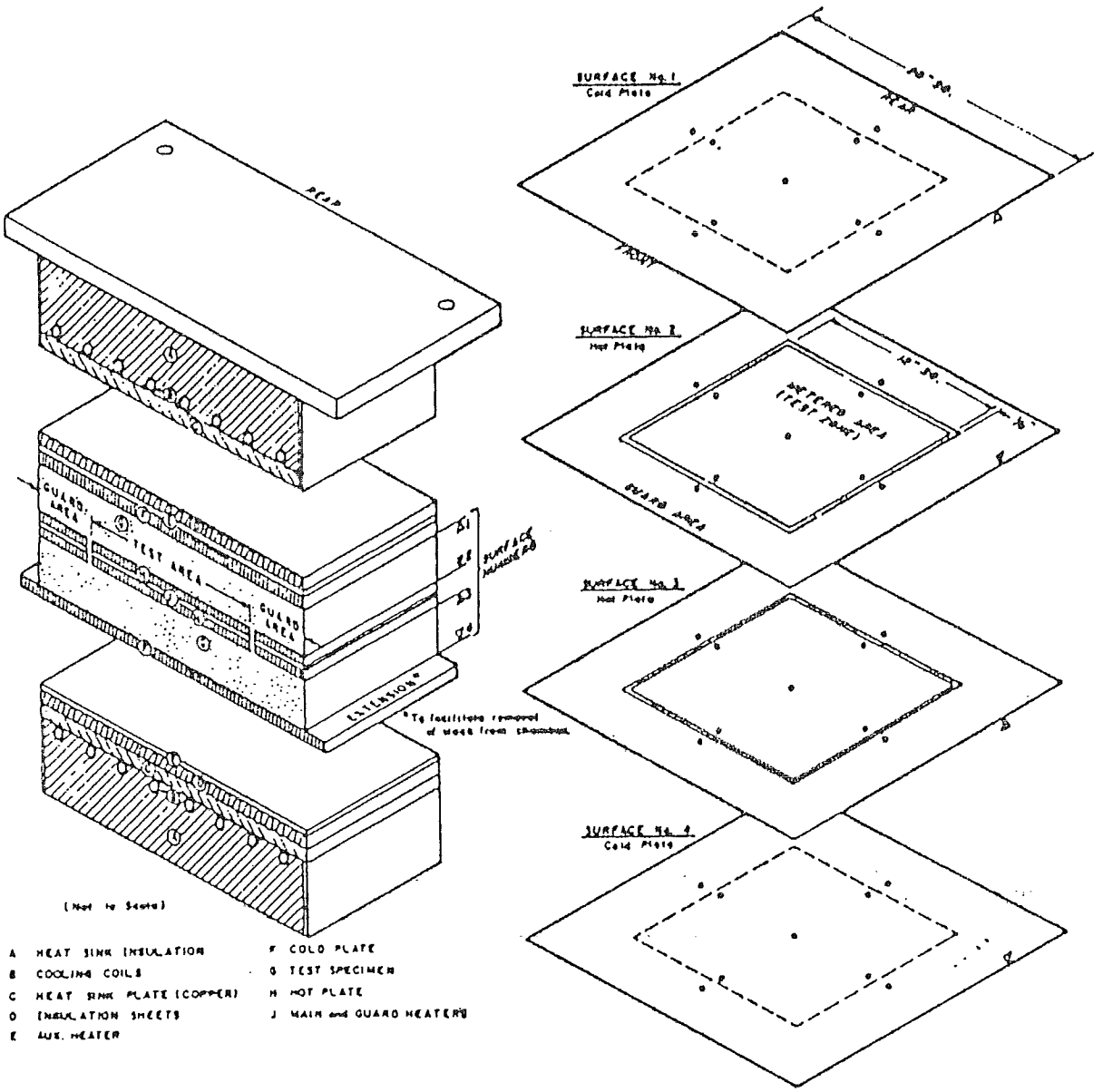


FIGURE 3.6.1 Diagram of Instruments Used for Probe Tests. (after Weschler, 1966)



a. *Stack assembly cross section.* b. *Thermocouple locations (•) in plate surfaces.*

Cross section of stack assembly and thermocouple locations in plate surfaces.

FIGURE 3.6.2 Guarded Hot-Plate Thermal Conductivity Testing Apparatus (ASTM Designation C177-71) (from Kaplar, 1971).

Q32-3

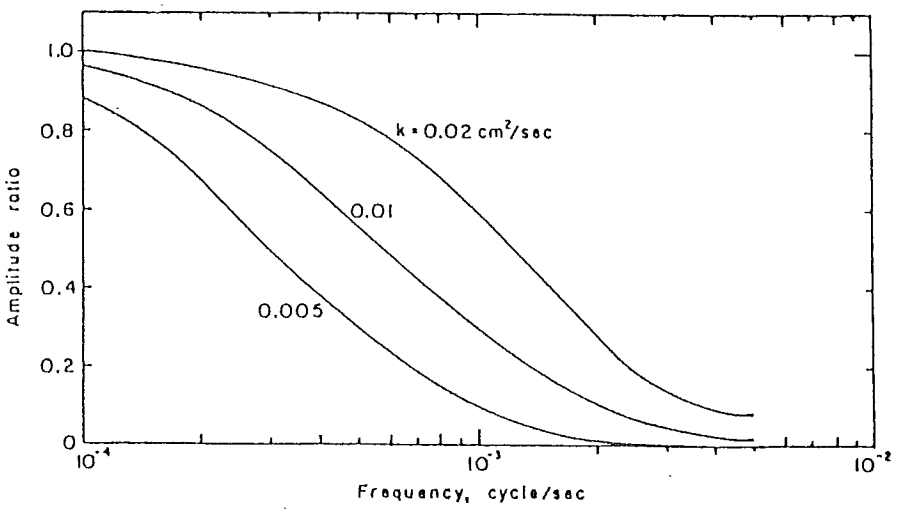


FIGURE 3.6.3 Ratio of the Amplitude of the Temperature Waves at the Periphery and in the Center, Sample (after Hoekstra, et al, 1973)

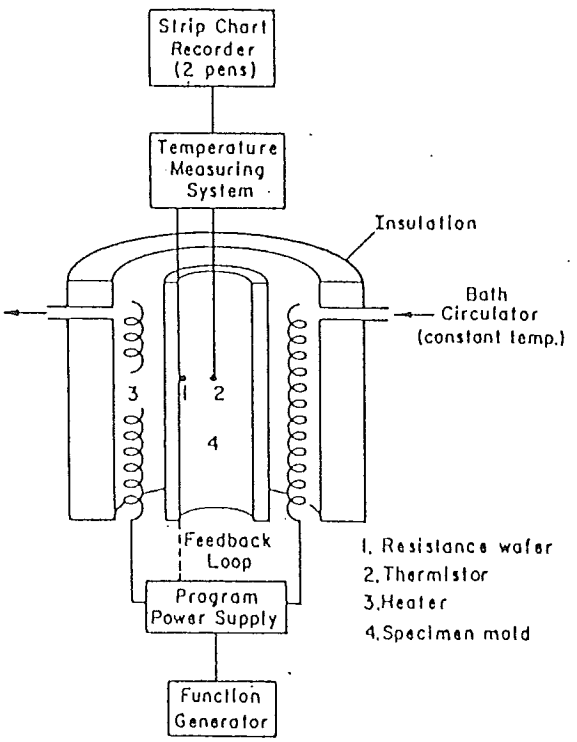


FIGURE 3.6.4 Apparatus (after Hoekstra, et al, 1973)

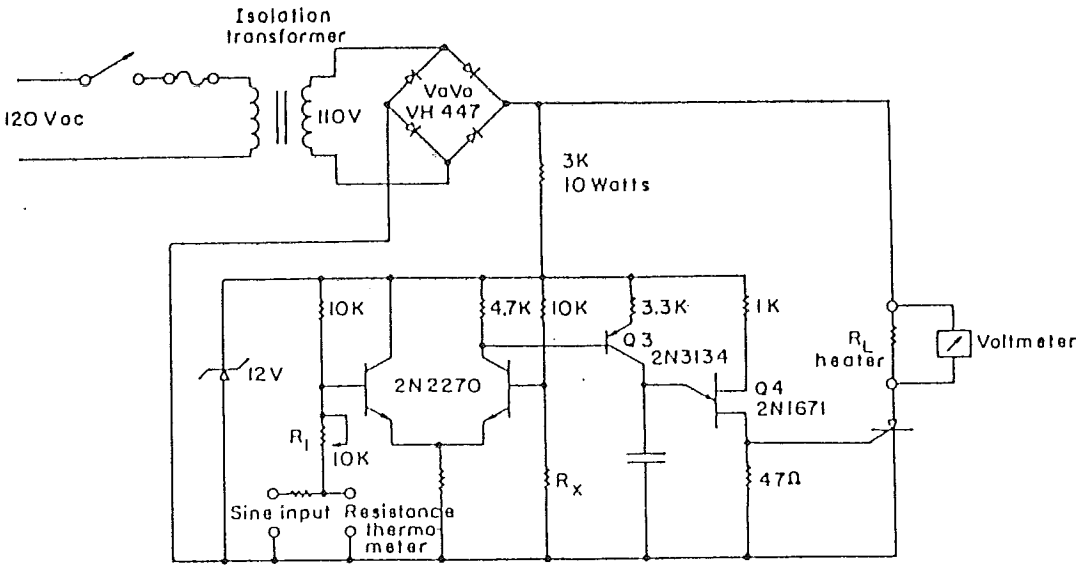


FIGURE 3.6.5 Circuitry of Programmable Power Supply (after Hoekstra, et al, 1973)

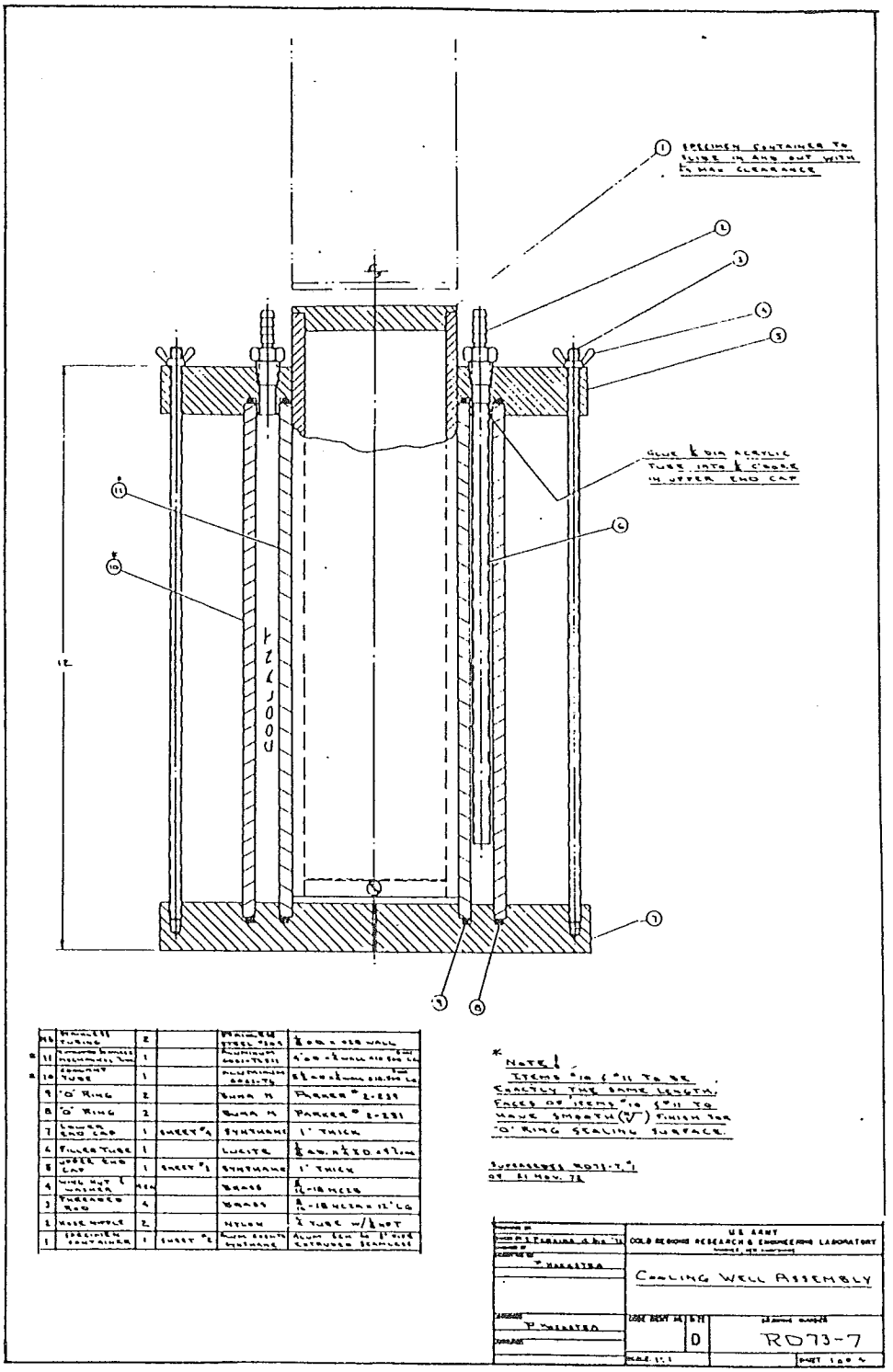


FIGURE 3.6.6 Machine Drawing of Sample Holder and Mold
(after Hoekstra, et al, 1973)

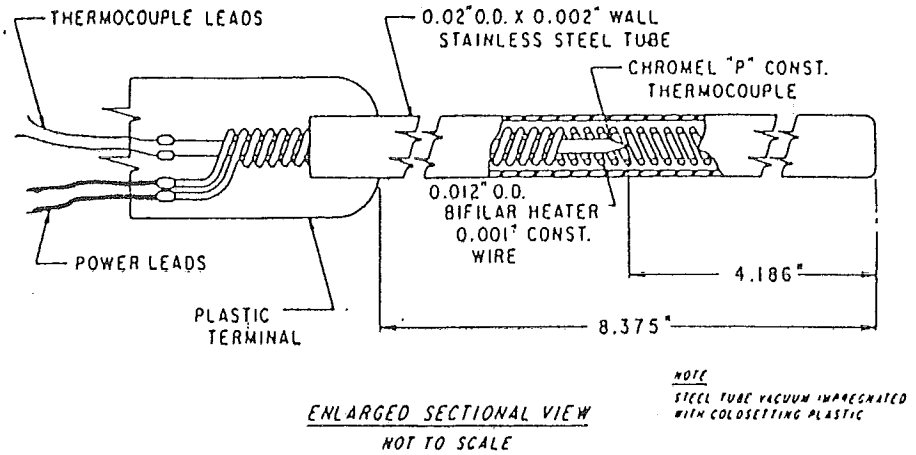


FIGURE 3.6.7 Schematic Diagram of Thermal Probe (courtesy Custom Scientific Instruments, Inc.) (after Penner, et al, 1975)

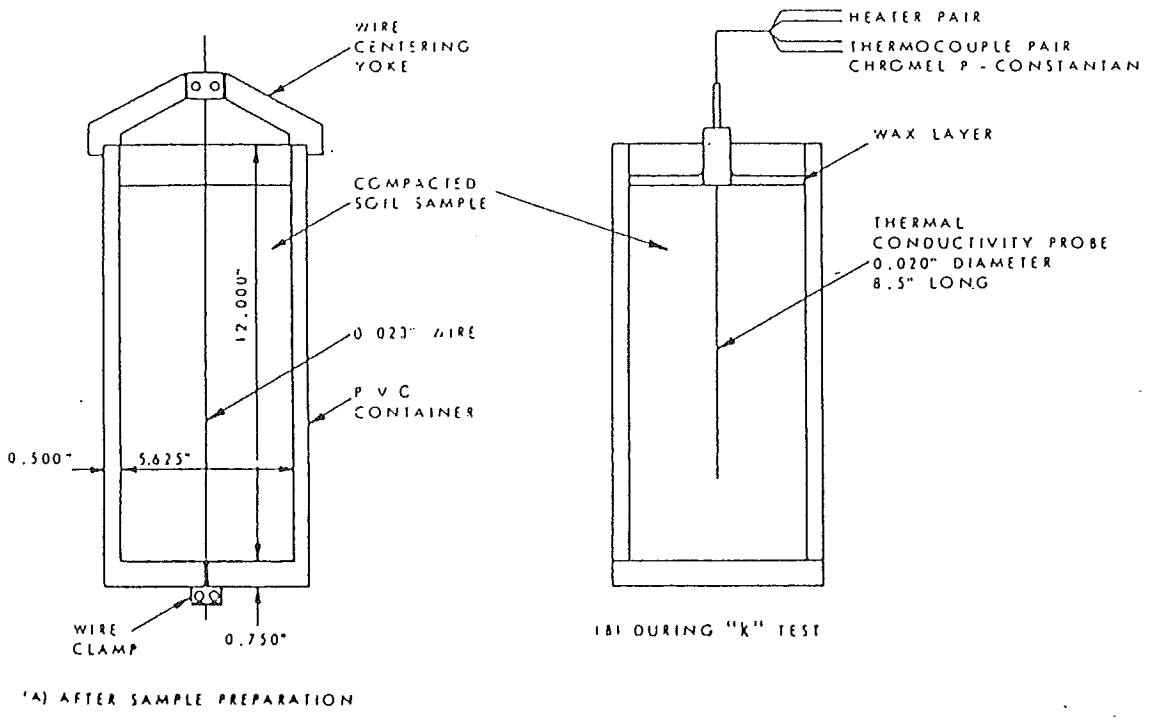


FIGURE 3.6.8 Soil Sample Mold (after Penner, et al, 1975)

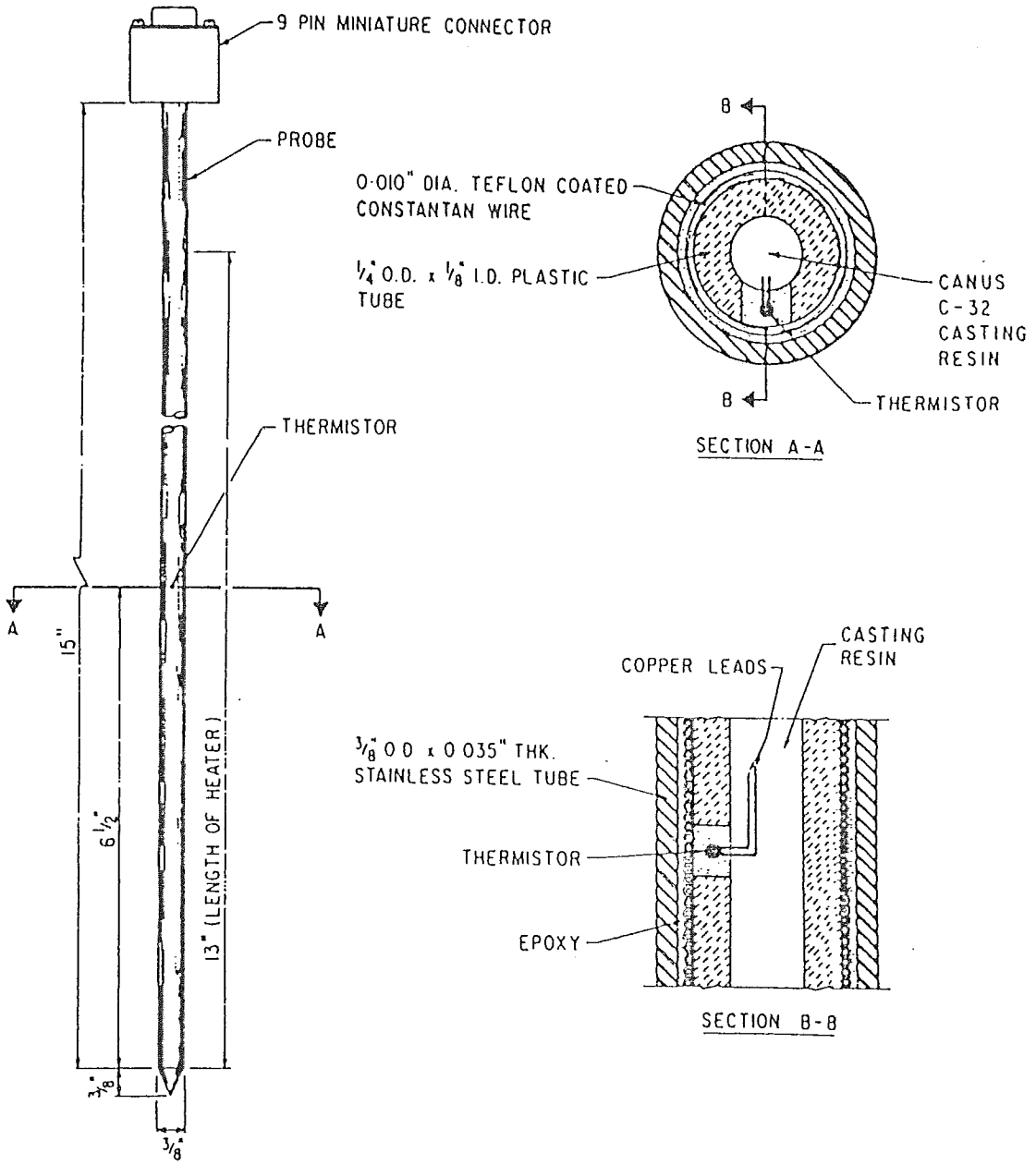
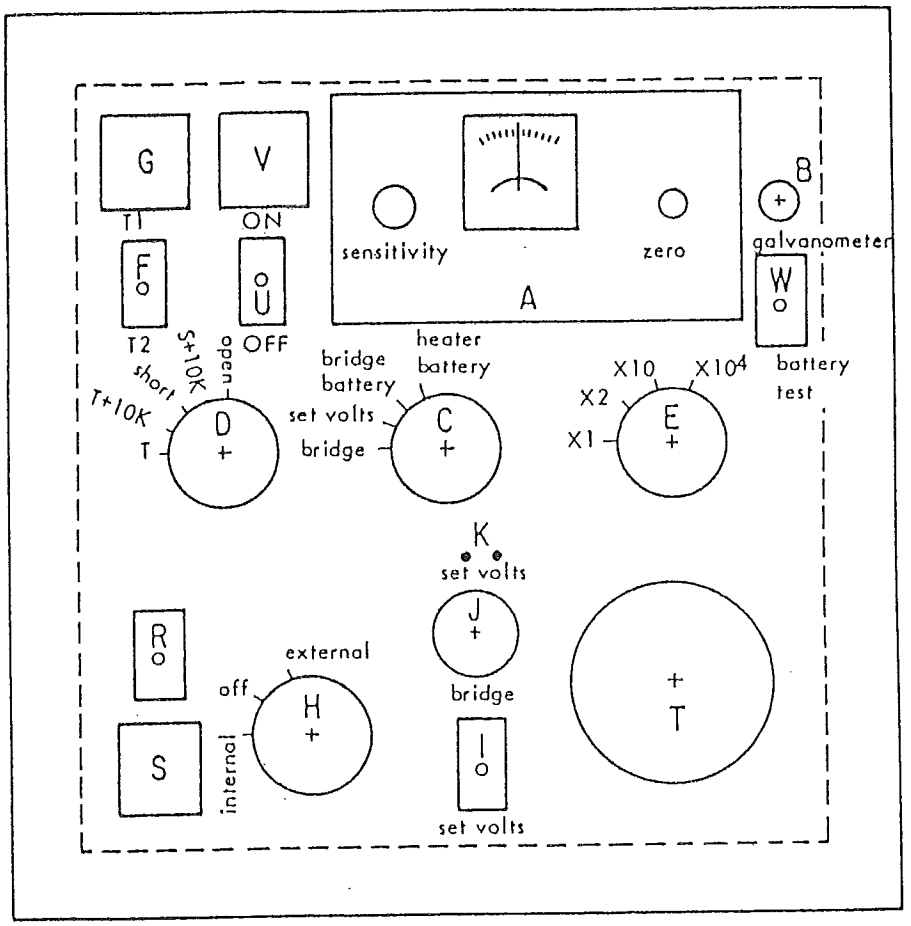


FIGURE 3.6.9 Thermal Conductivity Probe (after Slusarchuk and Foulger, 1973).



A LEEDS AND NORTHRUP MQ 2437 DC NULL DETECTOR

B GALVANOMETER TOGGLE SWITCH

C GALVANOMETER INPUT SELECTOR

D BALANCE ARM SELECTOR

E RATIO ARM SELECTOR

F THERMISTOR SELECTOR

G THERMISTOR INPUT 5 - PIN JACK

H BATTERY SELECTOR

I SET - APPLY BRIDGE VOLTAGE

J ADJUST BRIDGE VOLTAGE

K CHECK BRIDGE VOLTAGE

R REVERSE BRIDGE VOLTAGE

S EXTERNAL BATTERY INPUT - 9 PIN JACK

T 12KΩ DECADE

U HEATER ON-OFF

V HEATER OUTPUT - 2 PIN JACK

W GALVANOMETER BATTERY CHECK

FIGURE 3.6.10 Schematic Drawing of Front Panel of Bridge and Heater Unit (after Slusarchuk and Foulger, 1973).

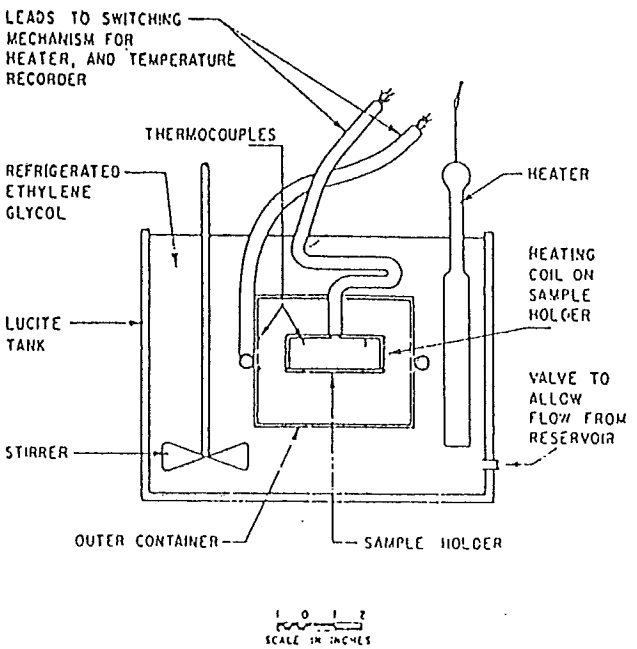


FIGURE 3.6.11 The Calorimeter (after Williams, 1964).

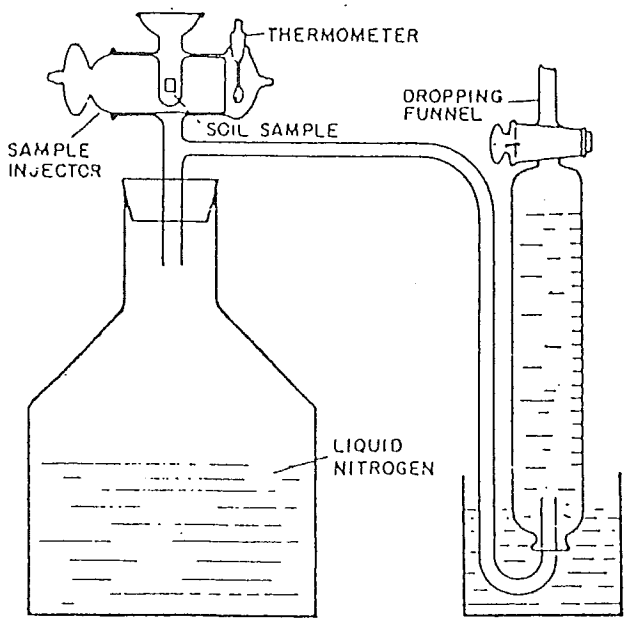


FIGURE 3.6.12 Low Temperature Calorimeter (after Wolfe and Theime, 1964).

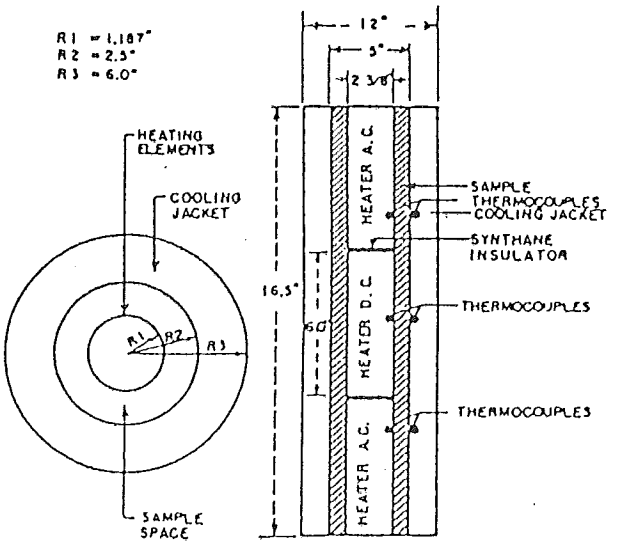


FIGURE 3.6.13 Dimensional Sketch of Test Equipment (after Wolfe and Theime, 1964).

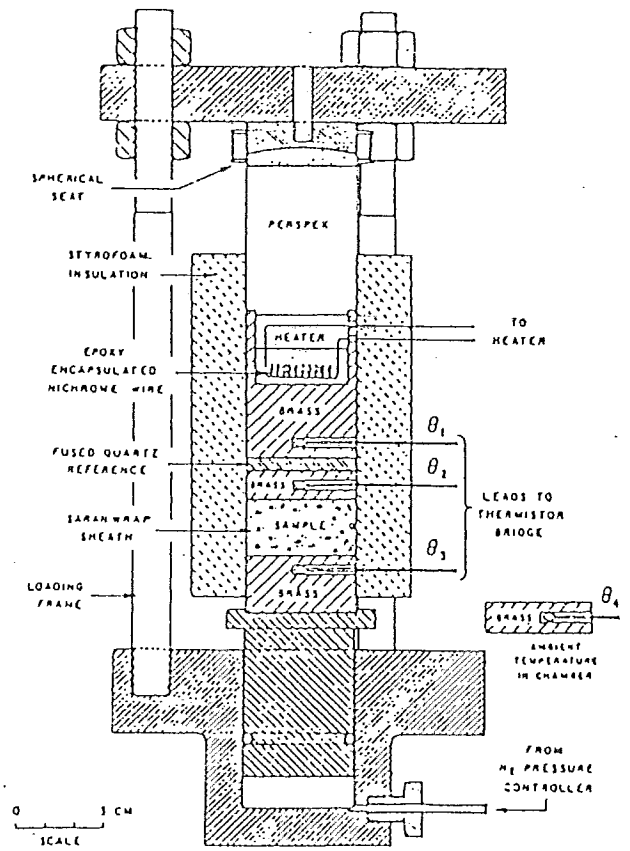


FIGURE 3.6.14 Divided-Bar Thermal Conductivity Apparatus (after King, 1978).

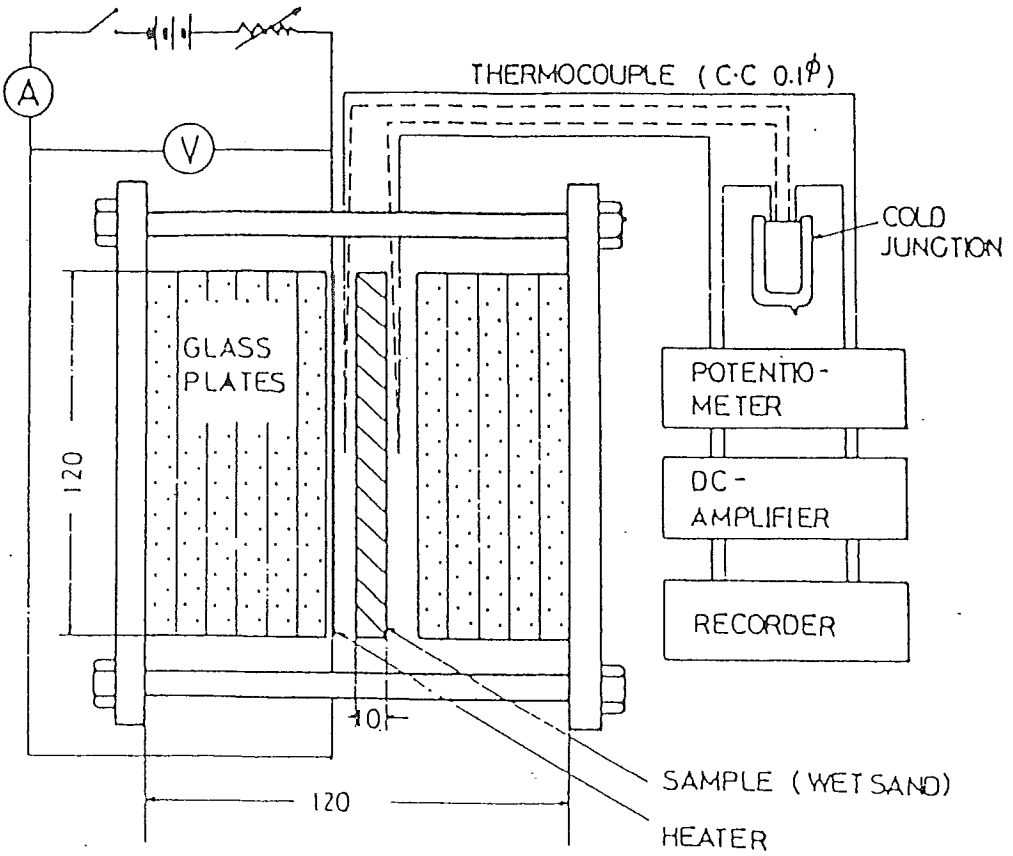


FIGURE 3.6.15 Measuring Apparatus (after Katayama, et al, 1973).

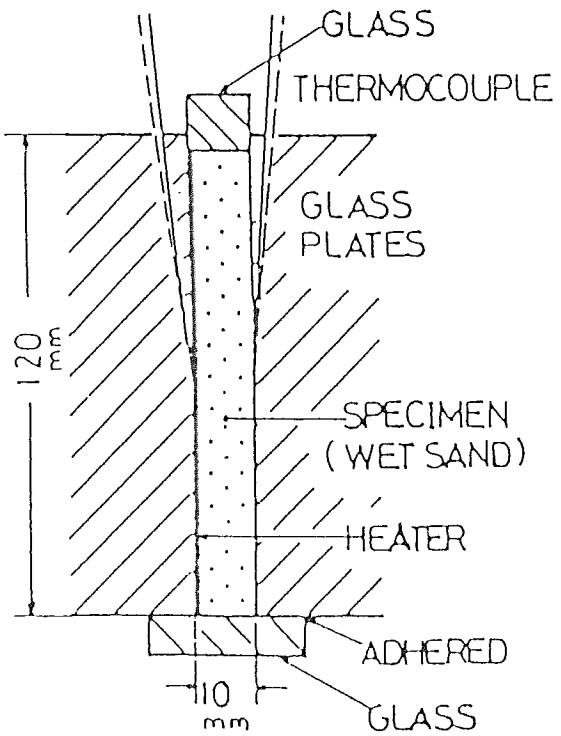


FIGURE 3.6.16 Details of Test Section (after Katayama, et al, 1973).

3.7 FROST SUSCEPTIBILITY AND FROST HEAVE TESTS

3.7.1 General

A review of frost action mechanics and theory, frost susceptibility index tests, and frost heave tests has been published by Chamberlain (1981a) and (1981b). Because of the thoroughness of that report, detailed descriptions of all of the various test procedures are not presented here. Descriptions of the preferred frost susceptibility and frost heave tests recommended by Chamberlain as well as other test procedures are presented in the following sections.

3.7.2 Frost Susceptibility Index Tests

3.7.2.1 Types of Frost Susceptibility Tests

According to Chamberlain (1981a), existing frost susceptibility tests may be divided into five categories, as described in the following paragraphs.

Particle-size criteria are widely used, and require information about the grain size distribution and Atterberg limits, as well as capillarity, hygroscopicity, permeability, and mineralogical information, in some cases. These criteria vary greatly with the jurisdiction involved, and are either pass/fail or degree type tests. The dependence of frost action on the pore-size characteristics of soils has been long recognized. Three methods have been used to determine the pore-size distribution of soils: The capillary rise method, pressure-plate method, and the mercury intrusion method. Characteristics of pore-size distribution curves found by these methods are used as indicators of frost-susceptibility.

Frost susceptibility criteria may be based on interaction of water and soil. Moisture retention tests, which can be related to frost heave, include variations on the pressure-plate apparatus (Williams,1966) and the osmotic suction device (Jones and Hurt,1978). Other tests include capillary-rise methods, critical permeability-suction tests, and the centrifuge-moisture test. None of these methods have been validated with field data.

Soil-water-ice interaction tests include the frost heave-stress test, used at CRREL (Hoekstra et al 1965), which measures the stress required to keep a sample at constant volume during freezing, pore water suction tests, and hydraulic conductivity tests. Again, there is little field evidence to validate such tests.

Frost heave tests, in which volume changes during freezing are directly measured, do not always adequately model field performance because of equipment restraints, such as side-friction, and problems in applying temperature changes. These tests may be used as indices of frost susceptibility. Variations in frost heave tests primarily involve the manner in which heat is removed from the sample: step changes in cold plate temperature with observations of frost heave with time (most commonly used test), a steadily decreasing plate temperature with measurement of the rate of frost penetration, and a constant rate of heat removal at the cold plate.

3.7.2.2 Requirements of Frost Susceptibility Index Tests

The purpose of frost susceptibility tests is to establish whether, and to what degree, a soil/rock will be affected by the freezing and thawing process. Such tests should establish the effects of parameters such as soil texture and mineralogy, pore size, rate of heat removal, temperature gradient, moisture conditions, overburden stress, and freeze-thaw cycling on frost action. Tests should be simple and reliable, be able to accommodate a wide range of materials and be per-

formed in a short time period. A test series must also establish both the effects of frost heave and thaw weakening, which are often independent of each other. Chamberlain (1981a) suggests that standard frost susceptibility tests be developed on four levels of complexity, so that engineers may select the appropriate test for their purposes. The test procedures recommended by Chamberlain (1981a) are outlined below.

3.7.2.3 Grain Size Distribution Test

The first widely accepted frost susceptibility criteria, proposed by Casagrande (1931), are based on the percentage of particles smaller than 0.02 mm and 2 microns.

The U.S. Corps of Engineers (1965) frost design soil classification system, presented in Table 3.7.1, is recommended by Chamberlain (1981a) as likely the best frost susceptibility index on the basis of soil grain size characteristics and Atterberg limits. Soils are classified as either non-frost susceptible (NFS) or with respect to the degree of frost susceptibility (F1--F4). The classification system is based on the results of frost heave tests (Linell and Kaplar 1959). The method is backed by a larger data base (mainly at CRREL) than other systems. This data base led to the development of a frost susceptibility chart in terms of percentage by weight finer than 0.02 mm, as shown in Fig.3.7.1. One disadvantage is that it does not account for thaw-weakening effects.

3.7.2.4 Moisture-Tension Hydraulic Conductivity Tests

Moisture-tension hydraulic conductivity tests give results characterizing the flow of water in soils, thus modelling all but the thermal dynamics of frost heave. The pressure cell permeameter, now in use at CRREL (Ingersoll,1981), is recommended by Chamberlain (1981a) to determine moisture-tension and hydraulic conductivity relationships.

The apparatus, shown in Fig.3.7.2, was designed to overcome the shortcomings of previous attempts to measure the parameters.

The procedure for this test, given by Ingersoll (1981) is summarized below:

(a) Equipment The soil sample is placed into a cylinder similar to that used in a constant head permeability test (ASTM D2434). The cylinder is made from clear plastic, with 7.62 cm inside diameter and 10.16 cm length. Porous stones are included in the top and bottom air-tight caps of the cylinder, each with Air Entry Values (AEV) greater than pressures to be administered during the test. Three-way valves connect the top cap to a constant-head water supply, and the bottom cap to a volumetric flask.

Two ceramic porous cups are implanted in the soil, 6 cm apart, through holes in the cylinder wall, and are connected to a water manometer which measures head loss between these points.

Air pressure is applied to the soil through several small 1 mm diameter holes in the cylinder wall and a series of grooves in the inside wall of the cylinder. An air pressure regulator and mercury manometer are connected. The 3-way valves are connected so that water may flow through both porous stones when the air pressure is changed.

(b) Sample Preparation The soil to be tested is first wetted slightly, placed in the cell in several layers and tamped to field density. The surface of each layer is scarified to improve soil pore continuity. The ends are trimmed and cylinder and soil are weighed.

The end caps are placed on the cylinder, keeping the porous stones as dry as possible.

The assembly is placed in a vacuum jar and evacuated for four hours. De-aired water is drawn into the sample under vacuum until the top cap is immersed. When saturation is complete, the cylinder is connected to the rest of the system. The valves and tubes are filled with water, ensuring that air is kept out of the system. Manometers should be thoroughly cleaned and calibrated before connecting to the system to minimize head loss measurement errors.

(c) Test Procedure After the sample is saturated, a conventional, saturated, constant head permeability test is performed. Upon completion of the test, the three-way valves are turned to allow flow through both porous stones simultaneously.

The air pressure is increased by a predetermined increment, and all the water expelled from the discharge tube is collected, and the quantity recorded. A hydraulic conductivity test is run with the 3-way valves reset to allow water to flow from the water supply. (It is important to record all water intake and output during the test.)

The above procedure is repeated for each air pressure increment desired. Upon completion, all valves should be turned to prevent water from re-entering the system when the pressure is released.

3.7.2.5 Thaw-CBR Tests

The loss of strength during thaw is an important consideration in the assessment of frost effects on soils. There are few accounts in the literature of index tests for thaw-weakening. Repeated-load triaxial tests, as conducted at CRREL (Chamberlain et al 1979), provide specific values for deformation properties in the freeze-thaw cycle, but are too complicated to qualify as an index test.

Jessburger and Carbee (1970) developed a three-part procedure including the standard CBR test (ASTM D1883).

Test Procedure

The test procedure proposed uses a combination of three well-known tests with a few modifications. These tests are (a) compaction test, (b) freezing test, and (c) CBR test.

(a) Compaction Test

The samples were compacted according to the modified AASHO compaction procedure at optimum water content in a steel mold with a 6-in inner diameter and a height of 7 in. A spacer 2.5 in.thick was used, so that the height of the sample was 4.5 in. The sample was compacted in five layers with 55 blows per layer.

(b) Freezing Test

The following conditions are important in freezing the samples: (1) Design of the sample holder with regard to the temperature distribution and the wall friction, (2) Water supply, and (3) Temperature control.

For normal freezing tests, USACRREL uses polyacrylate (lucite) cylinders. The thermal conductivity of lucite is similar to that of soils. The tapered inside wall, in addition to a thin, one-piece, adhesive-backed Teflon liner, allows the sample to heave with a wall friction considered to be insignificant compared to the relatively high surcharge of 20 lb (= 0.81 psi = 0.056 kg/cm^2) used in all freezing and CBR tests. The soil was compacted in a steel cylinder with side dimensions equal to those of the lucite cylinder; a spacer 1 in. high was used to make the sample 5 in. high. A duplicate run on each soil is recommended. The water content of the compacted sample should be determined.

The soaking base plate was used only for the first soaking period of 24 hours when the sample, still outside the freezing cabinet, was connected to a free water supply. A filter paper, a coarse porous stone, a copper plate, and a weight to give a total surcharge of 0.81 psi were placed at the top of the sample during soaking and freezing.

For the freezing test, the base plate was modified to allow air to escape from the sample. The water level was held at the top of the sample during soaking and at the bottom during freezing and thawing.

The normal freezing procedure was modified in that the samples were subjected to several freeze-thaw cycles. Constant temperatures were maintained in the freeezing cabinet during each freeze or thaw period. This modification is similar to the durability test used for soil-lime and soil-cement mixtures and was introduced to simulate in situ conditions and to produce a more uniform 'weakened' sample. In contrast to the durability test, the freeze and thaw temperatures penetrate into the samples only from the top of the samples, which are surrounded by insulation. Factors including soil type can warrant changing the number of freeze-thaw cycles, inasmuch as the number of cycles influences the CBR test results, depending on soil type. In many cases three freeze-thaw cycles were found to be sufficient.

The duration of each freeze and thaw cycle can also be varied. In these experiments, freezing and thawing times were both set at 12 hours and were found suitable for most of the samples.

The temperature for freezing and thawing is controlled by the general rule that the samples are almost completely frozen and are completely thawed at the end of each corresponding part of the cycle. Although different samples have a range of thermal diffusivities because of differences in soil type and water content, a fixed cabinet temperature was chosen for all tests. The cabinet temperatures chosen were -15°C at the top and +4°C at the bottom during freezing and +20°C and +4°C respectively during thawing.

Recently Kaplar developed a small freezing unit for four samples, which is recommended if a timer is added.

(c) CBR Test

To determine the bearing capacity of the soil after freeze-thaw cycles, the CBR test was chosen. This test procedure is well known, and the equipment is available in every soils laboratory. The test can be easily performed, and it works on strong and weak, cohesive and noncohesive soils.

To obtain true penetration loads from the test data, the zero point of the stress-penetration curve has to be adjusted if surface irregularities or the initial concave-upward shape of the curve demands a correction. The correction procedure described elsewhere has been modified in the following manner:

1. For the correction of surface irregularities, the new zero point will be found by drawing a straight line through the points at 0.1- and 0.2-inch penetration.

2. For the correction of the initial concave-upward shape of the curve, the new zero point will be found by drawing a straight line through the points at 0.2- and 0.3-in. penetration.

The CBR at 0.2-in. penetration, with or without correction, is the standard value.

The surcharge that influences the CBR can be selected according to the weight of the pavement and other loads if required, but for comparisons among several soils the application of the same load is necessary. It is recommended that a 20-lb load be used for the CBR test as well as for the freezing procedure. After running the CBR test, the water contents of the sample at top and bottom should be determined.

3.7.2.6 Frost Heave Index Tests

Chamberlain (1981a) recognized the need for a frost heave index test that could model severe freezing conditions which would be simple and inexpensive to perform, and produce results that could be correlated with field conditions. The severe operating conditions would include saturation prior to freezing, freely available water, no surcharge, a critical rate of heat removal and a critical temperature gradient. The test would accommodate both remoulded and undisturbed samples, and should be readily adaptable to other conditions. The apparatus would have an adjustable surcharge, minimal side friction and radial heat flow, and precise temperature control on top and bottom.

None of the published methods met these requirements, so Chamberlain (1981a) proposed a new procedure. The new test would include a multi-ring freezing cell (MRFC), circulating-liquid-cooled cold and warm plates, an air cooled room or cabinet for multiple samples, variable surcharge and adjustable moisture tensions. The MRFC could be lined with a rubber membrane, or the membrane may be used alone, in order to minimize the problems with saturation under vacuum and grains falling between ring segments.

Chamberlain (1981a) also lists a number of recommendations for frost heave tests:

1) Samples should be undisturbed, where possible. Otherwise, disturbed samples should be compacted to the in-situ density.

2) Saturation of samples with degassed water under vacuum is the best method, however, soaking may be more practical for small laboratories.

3) Samples with both diameter and height of 15 cm are recommended to overcome grain-size effects, while minimizing sample volume.

4) The pore water tension should be near zero to simulate a high water table, but should also be adjustable by applying a vacuum to the reservoir or changing its height.

5) The surcharge should be variable to simulate field conditions.

6) Temperature control is best achieved by circulating a non-freezing liquid from controlled-temperature baths through the end plates. The MRFC should be insulated radially with foam insulation.

7) Heat-extraction rates should represent severe conditions, or actual field conditions.

8) The temperature gradient in the sample should be approximately 0.25^{o}C/cm.

9) At least two freeze-thaw cycles should be performed to model field freezing conditions.

Descriptions of frost heave test equipment and procedures are presented in Section 3.7.3.

3.7.3 Frost Heave Tests

3.7.3.1 Frost Heave Test Developed for Alaskan Natural Gas Transportation System (Northwest Alaskan Pipeline Company)

As part of the design for a buried pipeline to transport chilled natural gas from Prudhoe Bay, Alaska to southern markets, the Northwest Alaskan Pipeline Company has developed a laboratory test which is intended to serve as a basis for quantitative predictions of frost heave during a specified time interval.

The frost heave test equipment and testing procedure are described in a report to Northwest Alaskan by Battelle Columbus Laboratories (Battelle, 1981). The authors are grateful to Northwest Alaskan for permission to refer to this unpublished report.

A schematic of a representative frost cell design is shown in Fig.3.7.3. Fig.3.7.4 is a schematic representation of the frost heave test setup. The cell is designed to freeze the sample from the bottom up so as to minimize the potential for sidewall friction. Important elements of the cell design are as follows.

a) Test Equipment

i) Sample container with 101 mm ID and a wall thickness of 38 mm. Recommended container material is non-absorbent PVC, nylon, or plexiglass.

ii) Sample container barrel - 125-250 mm long.

iii) Insulation around the cell should result in a total minimum thermal resistance (R_t) of 19 per meter. Polyurethane is the preferred material with a thickness of 75-100 mm required depending upon sample container wall material and thickness. The exterior surface of the insulation should be protected by tape or walls of plexiglass or PVC.

iv) A piston bearing and guide surface such as a collar or post.

v) Cell and plates should have cooling passages located in the material such that no significant temperature gradients occur.

vi) Soil sample temperatures are measured by two arrays of thermistors installed 180^{o} apart in the cell walls. The first array of 11 runs from 0 to 12.5 cm in 1.27 cm spacing, and the second array of 10 runs from 0.63 to 12.06 cm in 1.27 cm spacing above the base of the sample. Each thermistor is recessed very slightly for protection. A metal sheath-type or glass-coated thermistor probe is preferred. Thermistors protected by epoxy are satisfactory if coated to seal out water and water vapor. The thermistor resistance measuring device and resistance-to-temperature conversion shall have a combined accuracy sufficient to determine temperature to $\pm$ $0.01^{o}C$. The thermistors should be calibrated before each test using an ice bath made of distilled water and ice made from distilled water. Data acquisition system drift with time will be determined once a week using an additional thermistor by performing measurements in a calibration ice bath. The measurement of the ice bath should repeat the original ice bath temperature to within $\pm$ $0.01^{o}C$. The cause of any deviation greater than $\pm$ $0.01^{o}C$ shall be determined, e.g., thermistor drift or data acquisition system drift. The cause should be corrected, or if not correctable during the test, the deviation should be recorded to allow data adjustment to account for drift.

vii) End plate temperature measurements should be made using thermistors installed in each end plate. If not bonded to the plates, the thermistors should be maintained in contact with the plate and shall be immersed in a thermally-conductive grease. Thermistor readout and calibration requirements are the same as for the cell wall thermistors.

viii) Heave measurements to be within $\pm$ 0.0025 mm by a dial gage. A LVDT may be used in addition.

NOTE: A data acquisition system was installed to record LVDT measurements of base plate temperature, cell wall temperature, air temperature in the cold room, as well as the heave data.

ix) The coolant system for the hot and cold plates is designed to cause the end plates to perform as relatively isothermal surfaces. The heat removal capacity should be sufficient to provide or remove heat at a rate which will maintain a uniform end plate temperature.

The coolant system must satisfy two criteria to meet these requirements:

- Sufficient control of coolant reservoir temperature
- Sufficient rate of coolant flow

A minimum flowrate of 1.3 liter/min must be maintained through each end plate. Flowrates should be monitored daily. Each plate of a test cell will have an independent cooling system (Hotpack Circulator). The coolant reservoir should be well mixed at all times by stirring and pumping, e.g., during nucleation and flow measurements to prevent stratification. It is also required that the cold room temperature be maintained within specifications (see below). Coolant lines exposed to ambient laboratory temperatures should be protected with at least 19 mm of foam wrap installation.

For ramped temperature tests, a linear temperature ramp generator (LTRG) is used to allow the coolant temperature to ramp downward at a preset rate. Both top and bottom plate coolant flows are ramped at the same rate to provide a constant total temperature differential across the sample.

Coolant lines in the cold room require somewhat less insulation, but line lengths should be minimized to reduce extraneous heat transfer. All cooling lines and valves are to be 9.5 mm ID to provide the proper flowrate.

x) The water supplied to the test sample should be measured with an accuracy of 0.1 ml. The burette is to be adjusted daily to maintain the external water level approximately level with the

top of the sample. A small quantity of light oil should be placed on the water surface in the burette to reduce evaporation.

b) Cold Room

The test cells should be installed in a cold room with an air conditioning capability sufficient to maintain the air temperature around each cell at 2.0°C (± 0.5°C). The temperature on two opposite sides in the prevailing air flow path of each cell should be measured at various locations to ensure uniform temperatures between the cells. In addition, one of these temperatures should be monitored continuously on a high and low alarm basis. When the room temperature exceeds the 2.5°C limit, the temperature should be recorded at 15 minute intervals (minimum) while outside the specified range. To maintain the required temperature range on each cell, it may be necessary to provide baffling or door strips at the cold room entrance. Baffles will be installed near the test cells to intercept direct cooling air. The exhaust from a Hotpack unit installed in direct proximity to the frost heave test cells should be ducted to pass through the cold room refrigeration unit before re-entering the cold room ambient air.

c) Test Procedures

(i) Sample Preparation

Undisturbed Samples

1) Sample is extruded and trimmed to size, if necessary, slightly smaller than cell i.d. to allow for sealed membrane installation. A silicone lubricant of specified viscosity will be applied between the membrane and the cell wall to minimize wall resistance.

2) Place sample into cell and put on load cap. Let sample and cell stabilize in cold room for 24 hours.

3) Consolidate at test pressure, and track and plot settlement. Consolidation should continue until the rate of secondary consolidation is less than 5×10^{-4} mm/hr for fine grained soil and less than 2×10^{-4} mm/hr for coarse grained soils.

4) With the cell set up for double drainage, place at least a 0.9 m head in burettes connected to both ends of the test cell. Allow water to migrate into the sample from both burettes for at least 12 hours.

5) Lower the burette connected to the top of the cell to place a 150 mm differential head across the sample, and measure the inlet and outlet flowrates as a function of time.

6) Maintain a 150 mm head by adding water, until the flowrates at the inlet and outlet are nearly equal.

7) Repeat (5) for a 300 mm head, whereupon completion it can be assumed the sample is completely saturated.

8) Raise the burette connected to the bottom of the cell, and plot the difference in height of the water columns (h) vs. time on a semi-log scale. This should yield a line with constant negative slope. Permeability can be calculated from the following equation:

$$k = \frac{(\text{slope})\, a}{0.87A}$$

where: a = burette cross-section
= length of sample
A = sample cross-sectional area
(slope) = slope of log h vs. t curve

Remolded Fine Grained Samples

1) Mix a slurried soil sample at a water content in excess of the anticipated liquid limit. Experience should indicate the initial dry weight of soil which will consolidate to the desired test length. Note: A tolerance of ± 3 percent is suggested for test sample length after consolidation (e.g., 100 mm ± 3 mm).

2) For partial consolidation outside the test cell:
(a) Load and consolidate to test pressure

(b) If soil can be handled, transfer to test cell and continue consolidation as specified in Step 3.

(c) For soil that cannot be handled at test pressure: consolidate outside the cell to the minimum pressure which will permit handling for transfer to the test cell. Complete consolidation in the test cell at twice test pressure and rebound to test pressure.

3) For test cells which can be loaded directly without partial external consolidation:

(a) at t = 0, load sample to test pressure

(b) at t = 2 hours, increase the loading to two times test pressure

(c) When the rate of consolidation becomes less than 0.005 mm per hour reduce the loading on the test cell to test pressure. Note: This rate should be confirmed to be within limits of secondary consolidation.

(d) Allow the sample to rebound until rate of rebound becomes less than 5×10^{-4} mm per hour, then begin the frost heave test.

Remolded Coarse Grain Samples

1) Screen out greater than 19 mm and replace with equal weight of material between the number four sieve and the 19 mm size.

2) Wet sample in pan.

3) Soak sample in water for at least 12 hours.

4) Place soil in 25 mm lifts in water in the cell, tapping lightly on cell to remove bubbles.

5) Make sure cell is flooded (overflow) and bubbles are eliminated.

6) Allow the sample to consolidate according to the remolded sample procedure with a rebound criteria of 2.0×10^{-4} mm/hr.

(ii) Sample Nucleation

Initiation of a frost heave test requires the introduction and maintenance of ice particles in the soil sample. This is accomplished by circulating a very cold fluid through the base plate to reduce rapidly its temperature well below the freezing point, and then raising the cold plate temperature back to the

test temperature for the cold plate, (T_c), once sufficient ice has been established. Ideally, the period of sub-cooling should be kept short to minimize the initial transient effects. In practice, however, it is unlikely that sample nucleation can be identically duplicated for each test.

Two-way valves or their equivalent are to be used to make the coolant flow switches as instantaneous as possible. All coolant lines should have circulating flow at all times.

1) Before starting nucleation, circulate coolant at the specified hot plate temperature (T_h) through both plates until all cell-wall thermistor temperatures are stabilized ($T_h \pm 0.01^oC$ over 1-hour interval).

2) Connect the nucleation bath to flow through the bottom plate.

3) Begin the nucleation with the coolant flowing through the top plate at T_h and the nucleation bath flowing through the cold plate at -15^oC.

4) Let the nucleation bath continue to flow through the cold plate until heave and water expulsion are observed in the test cell. If nothing is observed after 10 minutes, let the end plate temperatures restabilize and check the nucleation flow system.

5) After nucleation is observed, disconnect the nucleation bath and start coolant flow at the initial cold plate temperature (T_c) through the cold (bottom) plate.

6) For samples which are expected to have high rates of penetration (x 5 mmm per day), let the cell stabilize for 48 hours. Otherwise, 24 hours of stabilization is sufficient time to allow transient effects resulting from nucleation to damp out.

7) Begin test.

(iii) Freezing Procedures (After Myrick et al 1982)

Constant Temperature Method

Constant temperature tests, with fixed end-plate temperatures across a sample cell, were chosen for the initial tests in order to minimize the complexity of environmental control by keeping all test parameters constant.

Further consideration of the constant temperature tests revealed a fundamental cause for experimental uncertainty of this type of test. The ice segregation ratio (ISR), defined for a constant temperature test as being the total test heave divided by the final frost penetration, is based on an accumulation of effects from initial sample nucleation up through test termination. Theoretically, therefore, a repeatable result would require exact duplication of the test conditions from nucleation through termination. Aside from the difficulties in controlling the sample boundary conditions precisely, random factors such as nucleation characteristics could cause a significant variation from test to test over an extended period.

Ramped Temperature Method

In parallel with the above test development effort a linear temperature ramp generator (LTRG) was used to simulate more directly the conditions to which soil samples beneath a chilled pipeline are subjected. This device was designed to control the coolant bath temperatures and decrease them incrementally at a variable preset rate.

The ramped temperature test was selected because it more directly models the field case, in which heave is induced in each soil increment as a freezing front passes through it at a rate which is constant for that soil increment. The test procedure generally specifies that the sample end temperatures be reduced incrementally at the same constant rate, so the total imposed temperature gradient across the test sample remains essentially constant. Once the initial transient temperature response of the sample stabilizes and the frost front is established within the test cell, the frost front will continue to penetrate through the sample at an approximately constant rate (assuming a sufficiently slow ramp rate) until it is disturbed by end effects as it approaches the top of the sample. The incremental ISR is defined as the rate of heave divided by the rate of penetration during the linear portion of the test. Thus, the ramp test procedure offers several advantages relative to constant temperature tests: a more direct analog of in-situ frost heave of an incremental soil element at some distance beneath the chilled pipeline, interpretation of experimental results independent of initial sample thermal response and end-effects, and more precise definition of test duration.

(iv) Sample Breakout and Analysis

1) At the end of the prescribed test period, probe thawed end of sample, measure, and record unfrozen length of sample. Confirm depth of frost after removal from cell.

2) Photograph sample on opposite sides. For fine grain soils slice sample longitudinally and photograph again.

3) Determine water content of thawed and frozen parts separately and add for total sample water content.

4) Back-calculate initial water content based on final water content and from burette influx, or outflux.

5) The following index property tests will be run for each sample at the end of each test:

a) Density, wet and dry
b) Water content (Item 3 above)
c) Organic content
d) Grain size analysis (sieve and hydrometer)
e) Atterberg limits
f) Specific gravity
g) Unfrozen hydraulic conductivity, permeability (only if specified)

A salinity test should also be performed on a representative soil sample for each test. In the case of undisturbed samples, an unused portion of the extruded sample should be used. For remolded soil, each time a new batch is stirred, a portion should be retained for a salinity test representative of the entire sample. In addition, a mineralogical analysis should be considered, depending on the nature of the soil and the test results.

3.7.3.2 National Research Council of Canada Test

The National Research Council of Canada developed a frost heave test procedure, as reported by Penner and Ueda (1977 and 1978) and Penner and Walton (1974).

a) Test Equipment

Penner and Ueda describe a frost heave testing procedure for a modified test cell obtained from Northern Engineering Services Ltd. The test cell construction is shown in Fig.3.7.5. Modifications made to the cell were as follows:

(i) A separate pressure chamber was mounted on the top end of the cell to apply loads to the sample.

(ii) A spiral grooved metal backing plate was installed behind the porous plate to facilitate air bubble removal from the water supply system after the sample was consolidated.

(iii) A rubber O ring was placed in a machined groove around the porous plate to completely confine the water-saturated sample within the holder. The cylinder was lined with teflon, thus making piston movement relatively free from friction.

The test cell was designed to hold a sample 10 cm long and 10 cm in diam. The tests were conducted inside a temperature chamber where the air temperature could be controlled within $\pm 0.05^{o}C$. Thermocouples placed in shallow grooves around the inside walls of the sample holder so as to be in contact with the outside of the sample were used to monitor temperatures, determine temperature gradients and locate the $0^{o}C$ position within the sample.

NOTE: According to direct communication with the senior author, heave is currently being measured using a DCDT system, water intake and expulsion are measured with a lever apparatus, and the formation of ice lenses in the test samples is observed using X-ray procedures.

b) Test Procedures

Loading of the sample for the consolidation phase and confining the sample during the test was achieved by air pressurizing the chamber mounted on top of the freezing cell. A precision regulator was used to control the chamber pressure.

Aqueous slurries were prepared at moisture contents just above the liquid limit. In order that the stress history would be similar, the same consolidation pressure was used for all specimens from one soil. After the secondary stage of consolidation was reached, the pressure was reduced to the value at which freezing was to be carried out. The test cell

containing the sample was placed inside a Tenney constant-temperature chamber and allowed to establish thermal equilibrium at the warm-side test temperature. The selected step freezing temperature was then imposed at one end of the sample with a temperature-conditioned end plate. The other end of the sample had free access to bubble-free water through a sealed porous plate system. The external free water level was maintained at

the level of the porous plate inside the apparatus throughout the experiment. Unidirectional freezing was achieved by heavily insulating the cell walls. Freezing of the over-consolidated specimen was started when the stress condition had equilibrated with the applied load and its temperature was in equilibrium with that of the controlled chamber.

A methanol/water solution at a temperature of about $-10^{o}C$ was circulated through the cold-side heat exchanger of the cell to induce crystallization in the soil. The initiation of crystallization was indicated by a sudden temperature rise in the sample next to the heat exchanger. This usually occurred at around $-2^{o}C$. A preselected step temperature was then applied to the sample from a second methanol/water circulator tank through a series of interconnecting shut-off valves. Freezing was allowed to proceed without changing the temperatures of the chamber or the cold-side heat exchanger until the experiment was completed. The temperature distribution in the soil, water movement either into or out of the soil, and amount of heaving (if any) were recorded with a Hewlett Packard 2010 H data acquisition system.

The extent of moisture flow and heave at each stress level were determined on separate specimens. Normally four separate freezing runs were required to establish the stress/heave rate behaviour for any particular soil over the required range.

c) Comments

The heave tests were performed on sample of silt and clay, with sand contents varying from 0 to 62 percent. Penner an Ueda commented as follows on the behaviour of the remoulded samples in the tests:

When there is a positive total heave rate in a freezing run, although water may be expelled from the sample initially, the water flow must reverse from expulsion to intake provided the experiment is not terminated too early.

If the freezing plane penetrates through to the bottom of the sample and heaving occurs during penetration, there is a possibility that the expulsion of water observed is temporary. It would be incorrect to assume that the "shut-off" pressure had been exceeded (above which pressure no further heave would occur).

The cold-side temperature imposed on the sample has a significant influence on the constant heave rate observed at low pressures. At high pressures, when heave rates are low, the confining pressure has an overriding influence on heave rate.

Near the beginning, when the rate of frost penetration is fast (0.1 mm/min) the water influx is low; near the end when the frost penetration is an order of magnitude slower (0.01 mm/min), the influx of water is large.

Penner and Ueda (1978) conducted additional tests on the same soil samples described in their 1977 paper. From the tests, they made the following comments on freezing technique and interpretation of frost susceptibility:

1) The relation between frost heave and time is linear for test periods up to 3 or 4 days and is independent of frost penetration rate for a given step freezing temperature (-1.45^{o}C). A constant heave rate is easily achieved by this method.

2) The frost heave-time relation is independent of the ratio of in situ water and migratory water in ice formation. At the beginning, heave is totally from in situ water; when frost penetration stops, heave is from migratory water only.

3) The field overburden pressure anticipated need not be known in advance or simulated in the freezing test; the rates at other overburden pressures can be calculated or obtained graphically.

4) The cold-side freezing temperature used must be held constant to calculate the P/T ratio correctly. Any suitable freezing step temperature, however, can be used which can be conveniently produced by the available freezing equipment.

5) There is no wall adfreeze problem, hence there is no need for a tapered cell, or movable rings, etc.

6) As the relation between total heave and time is linear, the experiment can be terminated after a relatively short time. The

original ACFEL frost heaving experiments required 24 days to complete.

3.7.3.3 Tests Developed at U.S.Army CRREL

A) After Chamberlain and Carbee (1981)

(a) Introduction

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) frost heave test was originally developed for airfield pavement design by one of its predecessor organizations, the Frost Effects Laboratory, New England Division, U.S. Army Corps of Engineers. Since the early 1950's it has been used (with modifications) as the standard laboratory test procedure for evaluating the relative frost susceptibility of soils and granular base materials by the U.S. Army Corps of Engineers. This frost heave test is principally used to augment the Corps of Engineers (1965) Frost Design Soil Classification System, which is based on the percentage of particles finer than 0.02 mm and the soil type.

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

Soil samples are generally compacted to densities approximating field conditions, saturated, and frozen from the top down at a constant rate of frost penetration of about 1.3 cm/day. This rate is considered to be representative of frost penetration rates throughout a winter in the northern United States. Except for special closed-system tests (with no external source of water), an unlimited supply of water under a constant head is provided at the base of the test samples during freezing. The test duration was originally 28 days and the frost penetration rate between 0.6 and 1.3 cm/day. However, with the adoption of the 1.3 cm/day frost penetration rate, the test is now normally terminated at the end of 12 days.

(b) Description of the CRREL Frost Heave Test Equipment

(i) The Freezing Cell

The soil containers originally used were waxed cardboard cylinders and standard acrylic tubes, approximately 15 cm in diameter and 15 cm in height. Because of early side friction problems, a tapered cast acrylic cylinder was developed (Fig.3.7.6). It is tapered inside from 14.0 cm at the top to reduce the frictional wall resistance to frost heaving. Bottom and top caps are provided with porous stones to facilitate vacuum saturating. A special base which minimizes the trapping of air bubbles is used when saturating by soaking and when conducting the freezing test.

(ii) The Freezing Cabinets

The freezing cabinets used to conduct the CRREL frost heave test are located in a walk-in coldroom maintained at approximately $4^{o}C$. There are six cabinets in the coldroom. The cabinets' inside dimensions are approximately 48 cm square in plan and each can accommodate four samples up to 30 cm high (Fig.3.7.7). Each cabinet is heavily insulated on four sides and the top. The bottoms are made of an open metal grillwork which allows the bases of the soil specimens to be exposed to the ambient room temperature. A thermopane window on the front of each cabinet allows visual observations without disturbing the thermal regime within the cabinet. The tops are hinged to facilitate access.

Each cabinet is cooled separately by 185 W air-cooled refrigeration units placed outside of the coldroom. Cooling plates are located in the upper half of the cabinets on the inside walls. The temperature is set and maintained by electronic proportional temperature regulators, which control heating coils located on the underside of the covers. Fans, also located on the underside of the covers, are used to obtain temperature uniformity in the air space above the test specimens.

The cabinets are designed to operate at temperatures ranging from the ambient coldroom temperature ($4^{o}C$) down to approximately $-30^{o}C$. The cabinet air temperature can be maintained to within $\pm 0.1^{o}C$ of the set temperature and the coldroom temperature to within $\pm 2^{o}C$. The coldroom undergoes a 15-minute thaw cycle once every two hours during which the room temperature rises 2 to $4^{o}C$.

Four test specimens are placed directly on the grillwork on the bottom of each cabinet. The space between the samples is insulated with granular cork to minimize radial heat flow.

(iii) The Water Supply

Separate Mariotte vessels (Fig.3.7.7) are used to furnish water at a constant head to the base of each test specimen. These water supplies allow a visual observation of the influx of water during freezing while maintaining a constant head. Outflow of water cannot be monitored with this setup.

(iv) The Surcharge

With the exception of special tests, all specimens are frozen under a surcharge of 3.5 kPa to simulate a field situation of 15 cm of pavement and base. This load is applied by placing a lead weight on top of an aluminum plate firmly seated to the upper surface of the test specimen. The lead weight and the aluminum plate are kept 4 cm apart by four lugs so that air may freely circulate over the aluminum plate (Fig.3.7.7).

(v) The Temperature Sensing Equipment

Temperatures in soil specimens are measured by means of copper constantan thermocouples placed through the Lucite cell wall. The thermocouples are normally spaced at 2.5 cm intervals along the length of the specimen. They are inserted so that the thermocouple junctions are just in contact with the soil, except for the top and bottom thermocouples which are placed near the center of the specimen (Fig.3.7.6). The output of the thermocouples is automatically recorded by a data acquisition system located immediately outside the coldroom.

(vi) The Heave Measuring Equipment

Originally, direct reading dial gages positioned on top of the lead surcharge weights were used to determine the magnitude of the frost heave. Recently the dial gages have been replaced by DC electronic displacement transducers (linear motion potentiometers, Fig.3.7.7). The output of the LMP's is recorded along with the thermocouple outputs on the data acquisition system.

(c) Sample Preparation

(i) Material Preparation

All material received for remolded frost susceptibility testing is washed and screened through a 4.75 mm mesh sieve, regardless of its gradation. For coarser materials, such as gravels and

sands, the material larger than 4.75 mm is retained for future recombining at prescribed percentages. In fine-grained materials, such as silts and clays, clods of soil are broken by passing the material through the sieve. Representative samples of 4.5 to 6.5 kg (depending upon the density required) are thoroughly mixed. Materials containing cobbles or large stones are normally scalped at the 1.9-cm size and the portion removed is replaced by an equivalent weight of representative material larger than 4.75 mm. The sample is wetted to the desired water content, thoroughly mixed, sealed and allowed to stabilize 24 hours prior to molding.

(ii) Compaction

Although some undisturbed samples have been tested, soil specimens are normally prepared by compacting them in a steel mold having the same inside dimensions as the acrylic freezing cell. The inner surface of the steel cylinder is first lubricated with silicone grease to facilitate ejection of the specimen after compaction.

Two methods are favored for compacting specimens to the desired dry unit weight. Frequently, relatively cohesionless coarse-grained soils, such as sand and sandy gravel, are prepared by an adaptation of the Providence Vibrated Density method (Lane 1948). With this method, a predetermined weight of oven-dry soils is compacted in the steel cylinder by applying a 454-kg spring-loaded piston at the top and vibrating the cylinder with hammer blows on the side. The soil is then wetted to mobilize cohesion and is ejected from the cylinder. Fine-grained soils, such as very fine sands, silts, glacial tills, and clays, frequently are compacted by tamping according to the American Association of State Highway Officials (AASHO test procedure T 180-57 (1958)), in five layers with a 4.5-kg hammer and 46-cm drop. If it is requested that stone sizes up to 3.8 cm be used, three 5-cm-thick layers instead of five 3-cm-thick layers are used. The surfaces between the layers are always scarified to minimize any dicontinuity.

(iii) Saturation

The molded specimen is ejected from the compaction mold and transferred to a tapered, acrylic plastic freezing cylinder lined with a thin adhesive-backed Teflon sheet. A saturation base plate, containing a saturated porous stone and filter paper, is then attached to the base of the cylinder. A filter paper and porous stone is placed on the top of the sample and a 9-kg weight placed on the stone to minimize swelling. The sample is then placed in a 4^{o}C environment and connected to a free water supply with the water level set 2.5 cm above the bottom of the

sample. The water level is raised 2.5 cm per hour until it is even with the top of the sample, and then it is raised at 7.5-cm increments every 2-3 hours until it is 30 cm above the top of the sample. This condition is maintained for 48 hours or until free water is visible over the top surface of the sample. The sample is disconnected from the saturation apparatus and the degree of saturation is determined. Ninety percent or better of full saturation is required.

Saturation has also been done under a vacuum. Both ends of the freezing cell are sealed with acrylic plastic caps containing porous stones and filter paper. Nipples extending out from the center of each cap are connected to tubing so that air can be evacuated from the top of the sample and de-aired water can be drawn in from the base.

The first method is satisfactory for coarse-grained materials with few fines. The latter method is used more frequently for finer-grained soils.

(d) Test Procedure

(i) Freezing Test Procedure

Once the sample is saturated, the saturation caps are removed and a special freezing base is attached to the bottom of the sample.

This base is designed to ensure unobstructed flow of water during freezing. The thermocouples are then inserted through the cylinder wall and the sample is placed in the freezing cabinet. Four samples are usually tested together.

The sample is next connected to the water supply with the level set at 0.6 cm above the base. The surcharge plates and lead weights are placed on the exposed upper surface of the sample and a thin 15-cm-diameter by 5-cm-long rubber membrane is sealed to the surcharge plate and around the cylinder wall to prevent exposure and drying of the heaved portion of the sample during the test. The linear motion potentiometer is then installed at the top of the sample with the spring-loaded stem resting on the surcharge weight. The sample is then allowed to temper at $4^{o}C$ for 18-24 hours.

The sample is then frozen from the top down at a $0^{o}C$ isotherm penetration rate of approximately 1.3 cm/day. Nucleation of the sample is accomplished by rapidly lowering the air temperature in the freezing cabinet to $-7^{o}C$ and seeding the top of the sample through a hole in the aluminum plate with fine pulverized ice. When crystallization occurs, the air temperature in the cabinet is raised to $-1^{o}C$, and then decreased each day in decrements to

maintain a constant rate of frost penetration. The test is normally terminated after 12 days.

(ii) Test Procedure After Freezing

Upon completion of freezing, the specimens are removed from the freezing cells, weighed and measured. The force required to eject the sample from the freezing cell is measured to assess the magnitude of side friction that may have occurred during freezing. If the ejection force is greater than 14 kPa, a judgement is made as to whether to accept or reject the test results, depending on the uniformity of the observed heave rate. The samples are then split longitudinally; one half section is retained for photographing and visual examination of the size and distribution of ice lenses and the other half section is cut into 2.5-cm thick horizontal segments for determination of water content distribution.

(e) Presentation of Results

A full report describing the relative frost susceptibility of the material, including graphs of heave and frost penetration versus time, is provided on request. Fig.3.7.8 shows typical results. Other information supplied includes an after-freezing water content profile, a photograph of the frozen section, the grain size distribution curve of the material as tested, the soil classification and the initial and final unit weights, void ratios and water contents.

(f) Limitations

The 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. 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 1981a) recommended that a new test be developed to address these problems. This report suggests 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, that a CBR test be conducted after the last thaw to determine thaw weakening characteristics and that moisture and surcharge conditions be adjustable to simulate field conditions.

(g) Advantages

There are also some advantages to the CRREL frost heave test. This test has been conducted on more materials than any other reported in the literature. As a result there is a large body of data from which it is possible to make estimates of frost susceptibility without actually conducting the tests. A tabulation of this data has been reported by Kaplar (1974). More recently, this data has been catalogued in a computer file for easier access. All one needs to do to estimate frost susceptibility is match the grain size curve, Atterberg limits, and void ratio or dry density of the material in question with a similar material that has already been tested. Furthermore because the test ranks soils as to their relative degree of frost susceptibility, one can make decisions at various levels of risk. Finally, the most significant advantage of the CRREL direct frost heave test is that it works. It is reliable for determining the relative degree of frost susceptibility of soils and granular base materials.

B) Instrumented Soil Column, Ingersoll and Berg (1981)

Ingersoll and Berg installed tensiometers, heat flow meters, thermocouples and electrical resistivity gauges in a frost heave test column. The equipment was developed to assist in improving algorithms for a mathematical frost heave model and to identify the critical parameters affecting frost heave, such as surcharge, free water level, and hydraulic conductivity.

a) Test Apparatus

The soil was molded within a 100 cm long circular cylinder having a diameter of about 14 cm. The inside of the upper 15 cm of the cylinder tapered slightly and was lined with Teflon tape to minimize sidewall resistance to heaving. The top portion of the cylinder was detachable from the lower portion (Fig.3.7.9).

Thermocouples were inserted through the cylinder walls and into the soil at intervals of 1 cm in the upper portion and intervals of 2.5 to 10 cm in the lower portion. Tensiometers were placed

at 1.5 - 20 cm intervals depending on the test and location in the column. In early tests the uppermost tensiometer was 18 cm below the top of the column while later tests had tensiometers at the 5 and 10 cm depths. Additional thermocouples were installed adjacent to the 5 cm and 10 cm tensiometers.

A linear motion potentiometer (LMP) and a dial gauge were used to measure vertical movement of the sample surface. Water absorption by the soil was visually monitored using a graduated constant head reservoir. The reservoir was also used to control the free water level in the sample; i.e. the tests were conducted in the open system mode. In several tests, electrical resistivity gages were placed within the upper 15 cm to locate the solidly frozen soil. Surcharge on the soil was created by placing lead weights on a pedestal attached to the surface plate. A heat flow meter was recessed into the bottom of the surface plate contacting the soil. Data from the thermocouples, LMP, and heat flow meter were monitored hourly by a digital data collection system.

Electrical pressure transducers were attached to most tensiometers to allow monitoring by the data collection system and to minimize the amount of fluid movement to and from the soil. Negative pressure dial gages were attached to the tensiometers without transducers. The tensiometers with dial gages were usually placed near the bottom of the column and were read daily. Tensiometers within the zone to be frozen were filled with a 30% ethylene glycol and water solution.

Copper electrical resistivity probes were used in most of the tests. These probes were initially spaced 2 cm apart and later at 1 cm intervals from the surface of the column to the 16 cm depth. These devices were used to delineate the solidly frozen zone. They were especially of value when portions of the soil became isothermal. A higher resistance reading indicated frozen soil, whereas a $0^{o}C$ thermocouple reading does not necessarily indicate the boundary between frozen and unfrozen soil. Observations on the resistivity probes were made manually once per day using an oscillator and a digital multimeter (Fig.3.7.10). The resistance probes were later omitted as they probably retarded heaving of the soil.

Loose cork insulation was placed around the upper 17 cm of the column for the three tests using Fairbanks silt, and to the 50 cm depth for the remainder. Only the top surface was exposed to subfreezing temperatures, allowing one-dimensional freezing. In early tests this was accomplished by cold air circulation, later by use of a refrigerated surface plate. The ambient temperature of the room was maintained at $+4.5^{o}C$.

(b) Test Procedure

Tests were conducted at a constant frost penetration rate, a constant heat flow rate, or with 3 sequentially lower step changes at the soil surface.

The water level was varied between depths of 15 and 100 cm.

For each test, the 85 cm long base section was first compacted with soil at slightly above the optimum water content using a uniform compactive effort for each of several layers. The molded density was then determined and used as a criterion when molding subsequent top segments.

At the conclusion of each test, the upper 15 cm section of the cylinder, containing the frozen soil, was removed. The frozen soil was ejected from the cylinder, split vertically to expose ice lenses for photographs, and cut horizontally into sections about 2.5 cm thick for final moisture distribution and density measurements. Density was measured by coating the sections with ice and displacing their volume in iso-octane maintained at $-5^{o}C$. The upper cylinder was then compacted with new soil and placed on the column.

Prior to freezing, the water source was adjusted to the level desired for the free water table. The water absorption and moisture tension were monitored until equilibrium was reached. Due to the relatively high hydraulic resistance of the soil within the column, the free water level in the soil column usually dropped dramatically during most of the tests on the silt samples (Fairbanks and Chena silts).

When freezing was initiated, a rapid temperature drop was applied to the surface of the soil until nucleation was apparent. The temperature was then raised to the desired subfreezing temperature. This procedure was necessary to stop supercooling to a significant depth before nucleation. Supercooling caused frost penetration control to be very difficult in the early stage of the tests.

3.7.3.4 Test Developed at French Regional Road Research Laboratory

The French have developed a test which is described in the publication Frost i Jord (Livet, 1981).

(a) Installation

(i) Thermostat-controlled tank

The cylindrical tank used (Fig.3.7.11) was 40 cm high and 60 cm in diameter and was insulated on the sides and bottom with expanded polystyrene. It was filled with a mixture of water and glycol kept at a positive temperature in the vicinity of $0^{o}C$ by means of a coil in which flowed refrigerated alcohol, and a regulation system with heating resistors and agitator.

(ii) Freezing units

Each freezing unit (Fig.3.7.12) is made up of:
- a cylindrical cell in Plexiglas with a double wall designed to contain the sample and to insulate it by providing a vacuum between the two walls;
- a cylindrical tank in Plexiglas enveloping the preceding cell and containing the water used for supplying the sample through a metal grille fixed to the base of the cell;
- a hollow metal piston making it possible, by the circulation of refrigerated alcohol, to impose a negative temperature on the upper end of the sample.

The placement of the sample in the sampleholder cell is preceded by the introduction into the cell of a foam rubber tube lubricated on its two sides by silicone grease. This rubber tube minimizes the friction forces. The soil sample is compacted in layers in this tube which is equipped with a fence of metal rods removed after compacting. Its height is 26 cm and its diameter about 7.2 cm.

(iii) Monitoring and Measuring Devices

The refrigeration of the tank and of the pistons is obtained by the circulation of alcohol refrigerated by a cryostat having a refrigerating capacity of 1300 W at $-10^{o}C$.

Piston temperature regulation is provided by the cryostat itself, and tank temperature regulation by the control system.

The vacuum which allows the insulation of the samples is furnished by a single vacuum pump for the six samples.

The temperatures of the cold face of the samples, of the groundwater and of the tank are measured by means of thermocouples. To measure the heave of each sample, the movement of the piston placed at the top of the sample is measured. This movement is transmitted, by means of a nylon cord, a pulley and a counterweight, to the shaft of a circular potentiometer supplied by a

stabilized voltage source. A precision switch transmits to a dual-trace galvanometer recorder the signals furnished by the thermocouples and by the displacement transducers.

3.7.3.5 Test Developed at Transport and Road Research Laboratory, Crowthorne, England

The British have developed a frost heave test which is widely used in Great Britain. It is described in the publication Frost i Jord (Sherwood, 1981).

The test adopted at the Laboratory is based on one originally developed by Taber (1930) in the United States. Compacted cylindrical samples of the material under test are frozen from one end while the other end is in contact with free water maintained at a temperature slightly above freezing point. The heave is recorded over a period of 10 days.

a) Sample Preparation

The samples tested are 101.6 mm in diameter and 152.4 mm long. They are compacted at the maximum dry density and optimum moisture content (obtained from the results of a British Standard Vibrating Hammer compaction test (5)) into a cylindrical mould provided with slight taper for easy extrusion. Immediately after extrusion a waxed-paper sheet approximately 200 mm long and 350 mm wide is wrapped round the curved face of the sample and secured with adhesive tape to give an upstand of approximately 50 mm at the upper face. A "Tufnol" plastic disc is then placed on the specimen; this is 95 mm in diameter and is provided with a central recess 10 mm wide and 2 mm deep in one side to accommodate a push-rod 6 mm in diameter that is later placed in the recess. Finally the sample is placed on a ceramic plate 13 mm thick and 101.6 mm in diameter and of maximum pore size 110 microns, located in a copper collar (specimen carrier) 68 mm high and 105 mm diameter, which has a hole 75 mm diameter in the bottom.

b) Freezing Cabinet

The freezing chamber, which is designed to take nine specimens, is shown in cross-section in Fig. . The design in use until recently was such that the freezing chamber was part of a mobile test cabinet provided with wheels so that the whole unit could be wheeled into and out of a refrigerated room. A cold-room is an expensive facility to provide and has other drawbacks: The

latest specification for the test, which was published in 1981, calls for a self-refrigerated unit which has cooling coils placed in the walls of the test chamber and which is part of a cabinet having its own self-contained refrigeration plant (Figures 3.7.13 and 3.7.14).

Inside the freezing chamber is a removable wooden specimen container, the base of which is provided with nine holes into which the copper specimen carriers fit. The space between the specimens is filled with a coarse dry sand to a level slightly higher than the top of the samples. Vertical push rods 6 mm in diameter, supported by transverse metal bars in which they are free to slide, are located with their lower ends in the recesses provided in the sample cover discs (Fig.3.7.13).

When the specimen container is in position in the freezing chamber the upper surface of the ceramic discs are level with the surface of the water in a thermostatically-controlled electrically heated water-bath in the bottom of the cabinet. An overflow pipe prevents water from rising above the level of the plates and water can be added to maintain this level, either manually, or with a constant-level device fitted to the side of the cabinet (Fig.3.7.14).

The refrigeration plant and the cooling coils in the walls of the freezing chamber are so designed that the temperature of the air within the cabinet at a point 150 mm above the top of the sepcimens can be maintained at $-17\pm1^{o}C$ during the test and the temperature of the water below the specimens at $+4\pm0.5^{o}C$. When equilibrium conditions are attained this corresponds to a temperature of $-6.5^{o}C$ beneath the disc at the top of the specimens. The temperature conditions to which the specimens are subjected are designed to be close to those originally specified for the procedure based on the use of a coldroom (1).

c) Test Procedure

The compacted specimens are placed in the cabinet and the sand filling added. The transverse bars and push-rods are put in position and water added to the bath until overflow occurs. After 24 hours at room temperature further water is added to replace any absorbed by the samples. The push-rods are pressed firmly in contact with the discs on the tops of the specimens and the distance between the top of each rod and the transverse bar is recorded. The controls on the cabinet are then switched on.

After 24 hours the push-rods are again firmly pressed in contact with the discs and the protrusion of the rods above the transverse bars is again measured, any heave that has occurred being deduced by subtraction. If a constant level device is not

fitted, water at +4°C is added until overflow occurs. This process is repeated until the specimens have been subjected to freezing conditions for 10 days.

The specimen container holds nine specimens and it is usual to prepare three specimens of three different materials for one test run with the equipment. The mean heave at 10 days of each group of three specimens is the value that is reported. Where the individual results in the group of three are widely scattered the test is repeated using nine specimens of the same material to obtain a more reliable result.

d) Recent Developments

Jones (1981) reviewed the British TRRL test, compared it with the CRREL and NRC (Penner) tests and discusses the use of a self refrigerated unit to replace the need to do the test in a cold room. He also discusses the use of a 'Precise Freezing Cell' (PFC) whereby individual control of the top temperature (at -6°C ±0.1°C) is provided by a 19W Peltier unit, which is controlled at -6±0.5°C by circulating anti-freeze. Further details of the PFC and commentary on the TRRL test are presented in Jones' paper.

3.7.3.6 Test Developed at University of Washington

A frost heave test developed at the University of Washington is described in a paper by Sherif, Ishibashi and Ding (1977). The authors' purpose in conducting laboratory tests of the heaving properties of silty sand was to establish a quantitative relationship among several variables including temperature, percent fines (< 0.02 mm), freezing time and heave. The test equipment and procedure are described below.

a) Freezing Cell

The freezing cell consists of a slightly tapered, vertical inner wall made of rolled acrylic cylinder. The cell is 30.5 cm in height with a porous stone supported 5.1 cm from the bottom by a

plexiglass base plate. The inner diameter of the cell is 11.35 cm at the top and 12.62 cm at the bottom. This allows the soil to settle down with ease during the thawing process, thus making it possible to more accurately determine the effects of various freezing cycles on soil heave. The cell allows a maximum specimen height of 25.4 cm and is instrumented with four thermocouples, one at the top of the porous stone and the remaining three placed at 2-in (50-mm) intervals up the vertical side wall. There are four openings at the bottom of the cell, below the plexiglass base plate, to allow free drainage (see Fig. 3.7.15 for details).

b) Insulating Cabinet and Water Reservoir

The freezing test procedure requires that the test specimens be initially cooled to a temperature of $+4^{o}C$. The freezing is conducted in an open system whereby the water at the base of the specimen remains at $+4^{o}C$ while the freezing temperature is

applied to the top of the specimen. The freezing temperature is obtained by placing the specimen in a walk-in type cold room. This procedure requires the use of an insulating cabinet to hold the specimens and keep the water reservoir at the desired temperature.

The insulating cabinet consists of an outer plywood box (75 cm by 79 cm by 20 cm) that supports and protects the styrofoam insulating box. Inside the insulating box, there is a sheet-metal pan (61 cm by 61 cm by 8 cm) that serves as the water reservoir and can accommodate six freezing cells. The underside of the pan is equipped with electric heat tape (ELECTROWRAP) and a thermostat-sensing bulb for temperature monitoring and control. A 24-point thermocouple board is attached to the outside of the insulated cabinet. A small circulating fan is installed inside the cabinet to circulate the water in the reservoir continuously. This helps to maintain a more unform temperature distribution within the reservoir (see Fig.3.7.16 for details). The aforementioned freezing cells, insulating cabinet and water reservoir were designed and built at the University of Washington.

c) Temperature Measuring Device

The temperature in the soil specimens is measured by copper-constantan thermocouples placed in the soil specimens at desired points as shown in Fig.3.7.15. The thermal electromotive force produced by the thermocouples is measured electrically by instruments consisting of an ACROMAG (Model 345, Type T, copper-constantan) 25-channel thermocouple reference and Esterline Angus (Model E1124E) multipoint recorder located outside the cold room. Temperature can be read on the recorder to 0.1^{o} accuracy.

The temperature of the cold room is controlled by a Honeywell Servoline Pneumatic Program Controller that continuously measures, records, and controls the cold-room temperature at the desired level. A check on the cold-room temperature was done by inserting a thermocouple into a 500-ml beaker filled with Ethylene Glycol. The thermocouples used in this testing program are made up of thermo-electric nylon-insulated copper-constantan thermocouple wire (NN24T). The measuring junction is formed by the use of QUIKTIP thermocouple pressure connector. This enables all junctions to be uniform in shape and size. The terminal blocks used on the outside of the insulating cabinet consisted of standard terminal blocks with copper and constantan terminal lugs inserted in the appropriate terminal to insure continuity in each thermocouple circuit.

Each soil specimen was prepared at its optimum moisture content by mixing with the proper amount of distilled water. The specimen was then sealed in a plastic bag and placed in the cold room at +4°C for a minimum period of 24 hr. The inner surface of the freezing cell was lubricated with silicone grease to minimize side-wall friction. The specimen was then molded in the freezing cell in four 2-in (50-mm) layers with a compactive energy equivalent to that of the Standard Proctor compaction test. The freezing cells, containing the specimens, were then placed in the insulating cabinet and allowed to soak for a period of 24 hr at the cold-room temperature of +4°C. Temperature of the specimens was recorded to insure a uniform temperature prior to freezing. The water level in the water reservoir was maintained at about 3/8 in. (9.5 mm) above the bottom of the specimen (top of the porous stone) at all times. The water temperature in the reservoir was kept at +4°C at all times.

The level of the specimen surface below the top of the freezing cell rim was measured and recorded prior to the lowering of the cold-room temperature to the desired freezing level. Once the cold-room temperature had attained the desired level, nucleation of the soil water was then initiated by seeding the specimen surface with fine pulversized ice. Temperatures of the specimens and the height of the specimen surfaces from the freezing cell rim were recorded periodically throughout the freezing period. The difference in the height of the specimen surfaces was the amount of heave.

The specimens were gradually frozen from the top to the lower level for 72 hr. Usually readings were taken and recorded twice daily during the freezing period. At the end of freezing, the cold-room temperature was raised to +4°C, and the specimens were allowed to thaw. The thawing period was usually 3 days; however, temperatures were recorded periodically until the

specimens had stabilized at about +4°C. At this point, the thawing period was completed and another freezing test started. The specimens were not removed from the cabinet or disturbed in any way during the thawing period. The process was continued until three freezing and thawing cycles had been completed. After that, the specimens were thawed and then removed from the freezing cells.

3.7.3.7 Tests Developed at University of Alberta

Several frost heave test programs have been undertaken at the University of Alberta. The most recent is described in the PhD thesis of Konrad (1980). The test description given in Konrad's thesis is given below.

a) Description of Equipment

The experimental apparatus is basically a modified oedometer designed for controlled temperature conditions. A schematic diagram of the equipment for a standard freezing test is given in Fig.3.7.17. At the beginning of this investigation, one freezing cell was available at the University of Alberta. Details of this cell are given by Mageau (1978).

The new experimental set-up has been designed for one dimensional freezing of a soil sample. The freezing cell is therefore placed in a controlled temperature room maintained at a constant temperature of approximately +1°C. However, defrosting cycles, which are necessary to prevent ice build-up on the refrigeration pipes cause slight temperature fluctuations of ±1°C. The use of a cold room helps to minimize radial heat flow into the soil specimen. The freezing cell is a 10 cm I.D. teflon lined cylinder. The outer jacket is machined P.V.C. pipe and provides lateral restraint during application of load. Insulation with a styrofoam cylinder around the P.V.C. pipe reduces significantly radial heat flow. One freezing cell has a 4 cm thick urethane foam layer around the outer wall of the P.V.C. pipe. The advantage of this type of insulation is that almost no preferential heat flow surfaces are created since the foam is sprayed onto the P.V.C. wall.

The top piston can be used either as a heat sink through which anti-freeze from the cold temperature bath is pumped or as a heat source maintained at a constant temperature above 0°C by forced fluid circulation. Moreover, it can also be used to transmit a pressure to the freezing soil. The applied pressure is obtained

by means of a hangar-weight assembly. The piston also allows the measurement of either the amount of heave or the heaving pressure that develops in a constant volume test. It slides freely in the cell since the I.D. is 9.8 cm. To measure the amount of heave, the rod from a displacement transducer (LVDT) mounted on the piston rests on the top of the P.V.C. jacket, so that any movement of the piston is measured by the displacement transducer. This device is accurate to ±0.025 cm. The output (in volts) is recorded on a data acquisition system.

To measure the heaving pressure, a load cell is installed between a rigid frame and the piston.

The bottom plate can be used either as a heat sink or as a heat source depending on the use of the top piston.

The temperatures at the top and bottom plate are controlled by continuous circulation of an anti-freeze/water mixture. The fluid temperature is maintained by separate Hotpack constant temperature baths. A high rate of pumping, 80 ml/s, minimizes temperature fluctuations at each plate.

During open system freezing tests, i.e. free access of water, the amount of water that goes into or out of the specimen is measured either by a sensitive differential pressure transducer or a volume change device when a back pressure is applied during freezing. In this latter case, the volume change is the only datum that cannot be monitored as an electric signal.

In an open system freezing test with no applied back pressure, the volume change in the burette is calculated from the change in water height monitored continuously by a very sensitive pore pressure transducer. This device was introduced by Mageau (1978) and proved to be reliable. Checks can be made periodically which improves significantly its reliability. The volume change in the burette can be obtained within $\pm$0.1 ml.

A freezing cell was designed to permit the application of a back pressure to the soil sample. Freezing with an applied back pressure to the pore fluid was conducted from the top downwards because the base plate provided good support for the pore pressure transducer as illustrated in Fig.3.7.18. The bottom seal was an o-ring and groove construction, effective to pressures above 400 kPa.

Thermistors are used for monitoring soil, top and bottom plate temperatures in the four freezing cells. The thermistors were calibrated with a Hewlett-Packard quartz thermometer accurate to

0.001°C. However, due to the inherent difficulties in calibration, it is expected that the temperature measuring system is accurate to only ±0.05°C. In general, four to six thermistors were sealed in the side wall of the cylinders to measure the temperature distribution in the soil specimen.

A fourth cell with sprayed urethane foam insulation, was equipped with a different type of temperature sensor. Five flat shaped platinium resistance detectors were installed in the side of the freezing cell and one at each heat exchanger plate. The advantages of the platinum resistance temperature detectors (R.T.D.) are a small sensing tip, rapid response time of the thermocouple, and fair precision. The dimensions of the R.T.D.'s used in this cell are 2.3 x 2.0 x 1.0 mm. The same calibration procedure as for thermistors has been adopted.

Experimental data are collected by means of a Fluke data acquisition system employing a digital voltmeter. The variable (temperature, heave, pore water pressure, heaving pressure, volume change) can be monitored at any selected time interval. The information, in volts, is stored on a cassette tape and is easily processed by computer.

Freezing from bottom upwards is strongly recommended when applied loads are used because it reduces lateral friction.

b) Sample Preparation

The samples were prepared as a slurry at a moisture content of about 50% to 60% (1.5 times its liquid limit). The slurry, which is a mixture of air-dried silt and deaired-distilled water, is allowed to stand overnight to permit saturation. The mixture is then poured into a vacuum desiccator. A vacuum of approximately 68 cm Hg is applied while vigorously vibrating on a shaking table for about one hour. This procedure removes nearly all entrapped air.

Consolidation of the slurry to 210 kPa is performed in three stages in a slightly undersized (9.7 cm I.D.) consolidometer. The water content after consolidation averaged between 27 and 30% and was relatively uniform throughout the specimen. Different heights of samples can be obtained depending on the amount of slurry poured in the consolidometer.

After primary consolidation is complete, the height and weight of the sample is determined. The specimen is then placed on the bottom plate of the freezing cell and a cylindrical rubber membrane is put over it. Both the teflon liner of the two hemispherical parts of the cell and the rubber membrane, are

coated with molybdenum powder, a lubricant, in order to reduce skin friction.

The permeability of some unfrozen samples, prior to freezing, was determined with a constant head permeameter at a temperature of about +0.5°C. This temperature corresponds to the average temperature in the unfrozen soil in freezing tests where one end is kept at about +1°C.

c) Freezing Tests Used in the Present Study

In general, three types of freezing tests were conducted:

1) Open system freezing tests with constant temperature boundary conditions. (These temperatures range from -5°C to -8°C)

2) Closed system freezing tests with applied back pressure, constant temperature boundary conditions and measurement of the pore pressure change.

3) Open system freezing tests followed by a closed system both with applied back pressure and under fixed temperature boundary conditions and measurement of the pore pressure change in the second phase.

The last two types of freezing tests may be too sophisticated for standardization (Konrad,1982,private communication).

Only one freezing test at constant soil volume during which the heaving pressure was monitored was performed.

Prior to freezing, the temperature in the sample is allowed to equilibrate at a uniform temperature above 0°C. Usually this temperature was approximately +1°C and a uniform distribution was achieved by keeping both boundary plates at +1°C.

Nucleation of ice crystals at one end of the sample is accomplished by imposing a negative step temperature on the soil surface. This is achieved by the circulation of a precooled liquid through the heat exchange maze. While the step temperature is maintained constant during freezing, the other extremity of the specimen is also maintained at a constant temperature above 0°C. These thermal conditions result in a penetrating frost front phase followed by the formation of a final ice lens with a quasi stationary frost front. Thus, these freezing tests create a period of decelerating frost penetration followed by a period

of stationary frost front during which a major ice lens can grow somewhere within the sample.

Some specimens were frozen in several stages by varying the temperatures at both plates at the end of each phase. This procedure results then in the formation of several major ice lenses, separated by an appreciable thickness of frozen soil.

Two closed system freezing tests with applied back pressure under different vertical loadings were conducted in a modified triaxial cell.

d) Collection of Data at the End of a Freezing Test

Upon completion of a freezing test, the sample is again weighed and its final height is measured. This allows a check on the amount of water drawn into the sample measured from the burette and of the amount of total heave obtained from the LVDT readings.

The thickness of the different zones in the specimen are also measured on the periphery. In the frozen part, it was decided to distinguish between a frozen zone with no visible ice, a zone of active lensing, and the final ice lens. The remainder of the sample is essentially unfrozen soil. Photographs were taken to record the structure of the frozen sample.

The specimen was then cut in two parts along a longitudinal axis. The position of the final ice lens is carefully determined from one part. Another important measurement is the accurate determination of the thickness of the final ice lens. This allows one to back calculate exactly the time of its formation using the measured total heave-time relationship. One can also verify if all the water entering into the soil flows to the base of the ice lens.

The longitudinal section of the sample also provides useful information on the amount of radial heat flow that occurred during the freezing test. If radial heat flow is negligible, the ice structure should be parallel to horizontal planes since the $0^{o}C$ isotherm penetrates horizontally downwards in one dimensional freezing. Radial heat flow, on the other hand, will produce slightly curved ice lenses, since the temperature along the sides of the sample will be warmer than that within the specimen in a given horizontal plane. Photographs were also taken of this longitudinal section.

The second half of the sample is cut into slices with a band saw kept in a cold room at $-5^{o}C$. The thickness of the slices

varied dependent on the ice structure. In the zone of active lensing, slices of about 4 mm thick could be cut. The position of each slice is determined and then the small soil portion is weighed and ovendried (105°C) to determine its water content.

3.7.3.8 Japanese Test Procedures

The Japan Gas Association has prepared a frost heave testing procedure in connection with LNG underground storage. The procedure is described in the manual - Recommended Practice for LNG Inground Storage (1979) - and is repeated below:

a) Apparatus

The apparatus shall have the following functions:

- It is possible to load a specified stress.
- It is possible to maintain the freezing rate constant and cause freezing from a specified direction.
- Apparatus for measuring the frost heave amount and the quantity of intake or discharged water is provided.

Explanatory Fig.3.7.19 shows an example of the apparatus for the frost heave test.

b) Specimen

The specimen shall be thoroughly saturated before starting the test.

The standard dimensions of the specimen shall be 6 to 10 cm in diameter and about 2 cm in height.

Explanatory Fig.3.7.20 shows a comparison between the test results obtained on a specimen 30 cm in diameter (D) and 25 cm in height (L) and an experimental formula obtained from a frost heave test on a specimen 6 cm in diameter (D) and 1.5 cm in height (L). There is no significant difference between the two cases.

c) Test Method

The test procedure for use of the apparatus shown in Explanatory Fig.3.7.20 is as follows:

i) Before starting the test, find the freezing temperature of the soil.

ii) Form the sample into the specified dimensions. Place filter paper on each side of the specimen and place the specimen in an acryl cylinder.

iii) Place the acryl cylinder on the cooling plate and insulate the outer surface of the cylinder.

iv) Saturate the specimen.

v) Mount the measuring apparatus for frost heave displacement and water intake or discharge quantity.

vi) Consolidate the specimen, until the settlement stops, at the pressure of the specified pressure plus 1 kg/cm^2.

vii) Remove 1 kgf/cm^2 and let it stand under the specified overburden pressure until displacement stops.

viii) Adjust the water level in the apparatus for measuring the water intake or discharge to the level of the top of the specimen.

ix) Lower the temperatures on the upper and lower surface of the specimen to the freezing point temperature of the soil.

x) Make the temperature of the lower cooling plate lower than the soil freezing point temperature to form ice cores at the lower end of the specimen.

xi) After confirming the formation of ice cores from the observed values of discharge of frost heave or water, return the temperature of the lower cooling plate to the soil freezing point temperature.

xii) Make the rate of temperature fall of the lower cooling plate constant, to maintain a constant freezing rate.

xiii) Measure displacement due to frost heave, and water intake or discharge quantity.

xiv) After the freeezing line has reached the upper end (end of freezing), maintain a specified temperature (-10°C) and confirm the end of frost heave.

xv) Measure the amount of natural defrosting settlement.

Further details about test procedures in use in Japan may be obtained in papers by Goto andd Takashi (1982) and Ryokai et al (1982).

3.7.3.9 Comparison of Laboratory Frost Heave Tests

In the publication "Frost i Jord" (1981), the frost heave test previously described in this report for three countries -- France (3.6.3.4), Great Britain (3.6.3.5), and the USA CRREL (3.6.3.3) -- are compared by P.Gaskin. In his paper he states the following:

> Laboratory test results have been compared to field behaviour in order to produce a frost susceptibility classification which can be used in road design. The test conditions in these three tests are summarised in Table 3.7.2. The ideal situation would be to have an identical frost heave test used in all countries, with perhaps different classifications to suit local conditions. At present, all three tests have significantly different conditions, and it is not possible to compare their classifications directly. The differences between the tests are discussed below, with some suggestions about the preferred test conditions. Ideally a simple frost heave test is needed that will differentiate between the frost susceptibility of different soils. Research engineers desire more information than would be required for a frost susceptibility classification needed by design engineers and there is a conflict between these two interests. The thrust of the comments given here will be for the simplest test possible to give a frost susceptibility classification. The reader is also referred to Chamberlain's (1981) review of frost heave tests.

a) Thermal Conditions and Control

> The American test specifies a constant rate of penetration of the zero isotherm. There are two objections to this. Firstly, extra instrumentation and control are necessary. Secondly, the rate of penetration depends on the thermal properties of the soil, and will be different for different soils under the same temperature conditions. Thus it is impossible to maintain the same rate of penetration in a test cabinet containing different soils. The British and French tests specify constant top and bottom temperatures, and this is the most satisfactory method.

The bottom temperature has to be above freezing to allow flow of water into or out of the sample. A temperature of around $+2^{o}C$ would be adequate. Top temperatures in the three tests range from about $-6^{o}C$ to $-17^{o}C$. This range appears to have been satisfactory, but some researchers have recommended that field thermal conditions should be reproduced in laboratory frost heave tests. More investigation of this suggestion is needed.

The British and American tests use circulating air to maintain the top temperature, and cold room or water bath temperature for the bottom temperature. These methods give rather large variations in temperature, and the French system of a circulating fluid in a top cap is better. Temperature control should be the same at both ends of the sample, and should be able to be maintained accurately. Temperature control by circulating fluid through both top and bottom caps is recommended.

Good lateral insulation is also required. The French vacuum system is good but complicated. Satisfactory lateral insulation could be provided using expanded polystyrene or similar insulation material with ambient temperature control probably required.

b) Water Supply

All three tests have the necessary open system freezing. The water supply head can be varied only in the American test. The capability of being able to apply different water pressures and of measuring the intake and output of water could be useful but is not essential.

c) Surcharge

The American test uses a small surcharge, the others use none. An increase in surcharge will cause a decrease in frost heave and different soils may be affected differently. The ability to apply a surcharge would be useful.

d) Friction Control

It is important that side friction is reduced to a minimum. Both the American and French tests are designed to minimize side friction and side friction must be a minimum in any standardised test. Chamberlain (1981a) suggested that some form of multi-ring cell was worth investigating.

e) Test Duration

All three tests take about ten days. However, it was reported that the freezing period in the British test might be reduced from ten to four days, and this would be welcome.

f) Sample Size

It should be possible to test fairly coarse road base material. The sample diameter in the French test is rather small and a sample diameter of 15 cm appears to be necessary.

g) Sample Preparation

All three tests use different compaction specifications, and one of these would have to be chosen for a standardised test.

The American test has a careful saturation procedure for the compacted sample, and a minimum of ninety percent saturation is required. In the British test, the sample stands with its base in water for 24 hours. However, a future modification was reported which would increase this to five days. This, it was stated, and been shown to increase the reliability of the test. The French test specifies compaction at a high water content in order to give a high degree of saturation. Good saturation is important, and saturation procedures should give a high degree of saturation, preferable checked, as in the American test.

h) Method of Reporting Frost Heave

The amount of frost heave occurring in the test is reported as total heave in the British test, as an average rate of heave in the American test and as the slope of the frost heave against the square root of the freezing index in the French test. There are two objections to the French method. Firstly, it is unnecessarily complicated. Secondly, it is based on a theoretical analysis of a constant cold temperature on the face of a semi-infinite medium, and this condition is not true for the duration of the test. A simple method of reporting the frost heave such as total heave or average rate of heave is adequate.

Finally, Chamberlain and Carbee (1981) make an interesting statement. They state that, because of the large amount of data collected from the CRREL frost heave test, it is possible to estimate the frost susceptibility without actually conducting the tests. It would be interesting if the British and French would send Chamberlain and Carbee soil properties of a number of soils that had been tested in their frost heave test. The American predictions could then be compared with the actual classifica-

tions made by the British and French tests, and some comparison of the respective classifications could be made.

In summary, reservations can be made about aspects of all three laboratory frost heave tests reported. It therefore appears to be worth developing a new simple and reliable frost heave test which incorporates the best features and omits the less desirable features of the existing tests.

3.7.4 Discussion

A large number of index and semi quantitative test procedures are available to assist in determining the frost susceptibility of a soil. Among the index tests, soil gradation and in particular, a criterion based on the percentage of soil particles smaller than 0.02 and 0.002mm, as proposed by Casagrande (1931), appears to be the simplest and most universally applied method for determining frost susceptibility. Other index tests, such as moisture retention tests and capillary rise methods, have little experimental history, or correlation with field experience, and are complicated to perform. However, for pavement and airfield design, one index test should be considered for more common use and possible standardization: the Thaw-CBR test (Section 3.7.2.5).

The laboratory frost heave tests described in Section 3.7.3 all have the capability of measuring frost heave in a controlled laboratory environment. Some of the tests (U.S.CRREL, British TRRL, French) are treated as index tests of frost susceptibility and no attempt is made to determine what the actual heave would be under field conditions. Other tests (Northwest Alaskan Pipeline Company, University of Alberta) attempt to control enough of the variables affecting frost heave that a quantitative prediction of the magnitude of frost heave in the field is possible. Few of these tests have been validated sufficiently in the field to confirm their potential for use as a universal frost heave test. However, the University of Alberta has been field validating its procedure (Morgenstern, private communication, 1983). In addition, the

Northwest Alaskan Pipeline Company is presently engaged in a comprehensive program of both laboratory and field frost heave tests. If satisfactory correlations are established over the next few years between the laboratory predictions and the field measured heaves for a variety of soil types, this test procedure should be considered for implementation as a test standard, perhaps with modifications to incorporate the best features of some of the other tests now in use. In addition, reference should be made to recent work at the University of Alberta, especially the mechanistic theory of ice lens formation that has been developed by Konrad and Morgenstern (1980), before finalizing and evaluating a standard procedure for frost heave tests.

When a standard frost heave test is developed, consideration should be given to the following aspects of the procedure and test equipment:

i) Friction between samples and container

Freezing from bottom up and use of lubricants are recommended to minimize friction. Other means of friction reduction, such as the use of stacked rings, should be considered.

ii) Sample surcharge

It should be possible to impose a pressure on the sample equal to the minimum value anticipated in the field.

iii) Temperature control

Temperatures should be controlled in the end plates to within approximately $0.02^{o}C$. Some improvement in current technology may be needed to achieve constant or constantly decreasing temperatures over the duration of a test. Sufficient insulation is needed around the cell to eliminate lateral temperature gradients. The equipment should be capable of imposing either stepped (sudden), or ramped (gradual) temperature changes, the nature of temperature change imposed depending on what is most relevant to the problem under study. As a general principle, the use of a gradually decreasing temperature is attractive

as interpretation of the test data is simplified by keeping the frost penetration rate and thermal gradient essentially constant. The test cell should be equipped with thermal monitors to permit the accurate measurement of temperature gradients along the length of the sample (accuracy of $\pm 0.02^{o}C$ suggested).

iv) Sample condition

Test equipment should be capable of accepting both undisturbed and remouled samples.

v) Sample saturation procedure

The presence of air in the sample may inhibit frost heaving and a procedure for ensuring a minimum saturation level (such as 95%) should be established.

vi) Nucleation procedure

Most procedures require an initial thermal shock to induce freezing, whereupon the sample is returned to a state of thermal equilibrium. A standard nucleation procedure should be established.

vii) Measurement of water intake and expulsion

Changes in pore water control should be measured and correlated with the measured heave.

Before making a decision to proceed with the formulation of a standardized frost heave test, it should be recognized that many national, provincial and state jurisdictions have acquired a considerable body of experience in relating their own particular tests and frost heave criteria to performance -- mainly for roads, railways and airfields. The justification for making major changes to presently accepted design practices to overcome frost heave phenomena will have to be a demonstrable improvement in predictive capability and ultimately that construction is feasible at a lower cost in materials that would be rejected under the current standards.

TABLE 3.7.1 U.S. Army Corps of Engineers (1965) Frost Design Soil Classification System (after Chamberlain, 1981a)

*Frost susceptibility**	*Frost group*	*Kind of soil*	*Amount finer than 0.02 mm (% by weight)*	*Typical soil type under Unified Soil Classification System†*
NFS**	None	(a) Gravels	0-1.5	GW, GP
		(b) Sands	0-3	SW, SP
Possibly‡	?	(a) Gravels	1.5-3	GW, GP
		(b) Sands	3-10	SW, SP
Very low to high	F1	Gravels	3-10	GW, GP, GW-GM, GP-GM
Medium to high	F2	(a) Gravels	10-20	GM, GM-GC, GW-GM, GP-GM
Negligible to high		(b) Sands	10-15	SW, SP, SM, SW-SM, SP-SM
Medium to high	F3	(a) Gravels	>20	GM,GC
Low to high		(b) Sands, except very fine silty sands	>15	SM, SC
Very low to very high		(c) Clays, PI > 12	—	CL, CH
Low to very high	F4	(a) All silts	—	ML, MH
Very low to high		(b) Very fine silty sands	>15	SM
Low to very high		(c) clays, PI < 12	—	CL, CL-ML
Very low to very high		(d) Varved clays and other fine-grained, banded sediments	—	CL and ML; CL, ML, and SM; CL, CH, and ML; CL, CH, ML, and SM

*Based on laboratory frost heave tests.

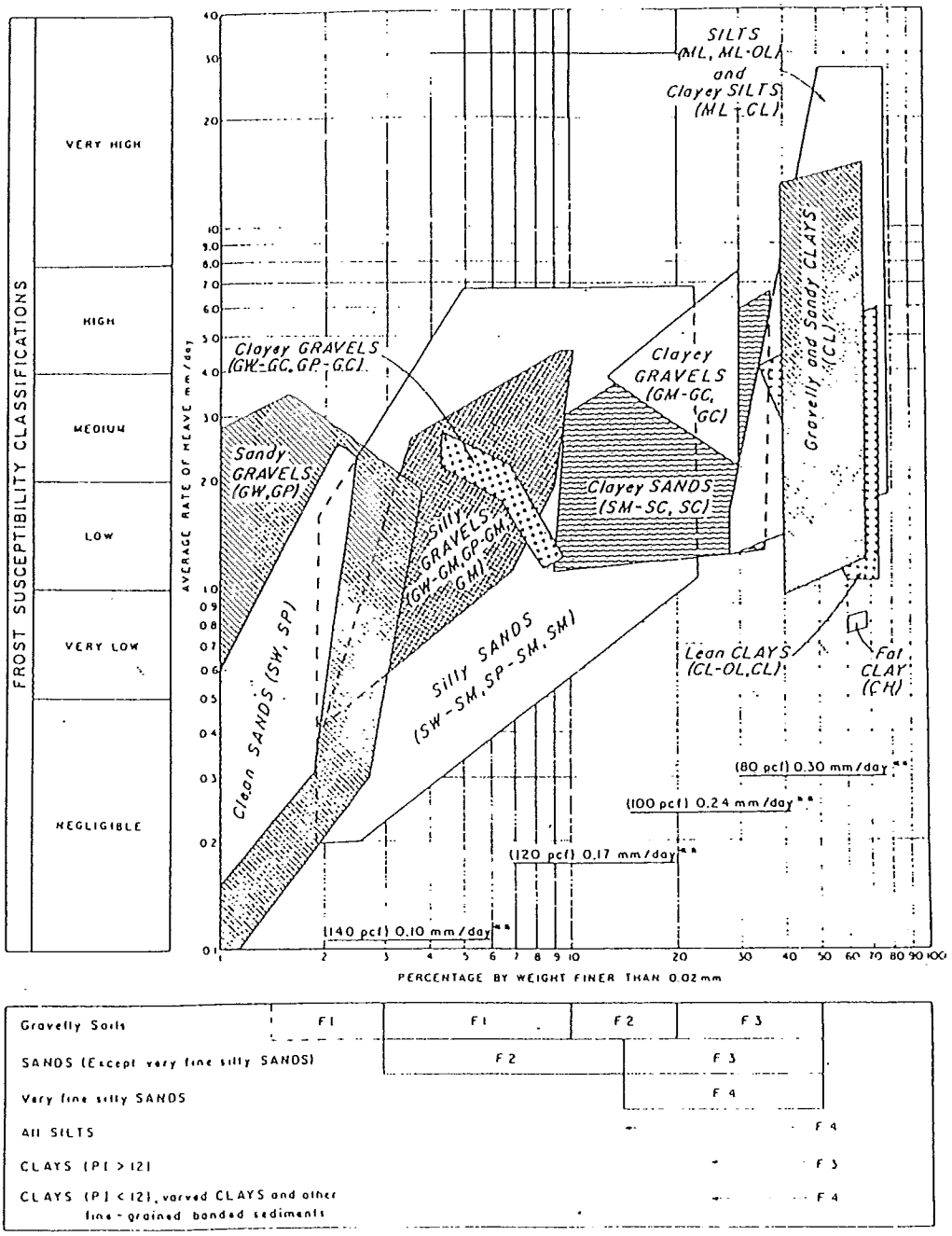
†G = gravel, S = sand, M = silt, C = clay, W = well-graded, P = poorly graded, H = high plasticity, L = low plasticity.

**Non-frost-susceptible.

‡Requires laboratory frost heave test to determine frost susceptibility

COUNTRY	FRANCE	GT. BRITAIN	USA
Reference	9	7	4
Sample hight, cm	26	15	15
Sample diameter, cm	7,2	10	15
Top temperature, °C	Not stated (-5,7 ref. 3)	-17	Varies
Bottom temperature, °C	+ ~ 0	+4	+4
Rate of penetration of zero isotherm, cm/day	Varies	Varies	1,3
Position of frost front at end of test	Within sample	Within sample	Bottom of sample
Duration of test, days	Not stated (10, ref. 3)	10 (possible change to 4)	12
Surcharge, kPa	0	0	3,5
No. of samples tested / unit	6	9	4
Method of reporting frost heave	Ratio of frost heave to square root of freezing index	Total heave	Average rate of heave
Temperature control at top	Circulating fluid in top piston	Circulating air above sample	Circulating air above sample
Temperature control at bottom	Water tank	Water tank	Circulating air in coldroom
Lateral temperature control	Vacuum	Sand	Cork insulation
Temperature profile observation	No	No	Yes
Friction Control	Foam rubber sleeve, lubricated with silicon grease	Waxed paper	Teflon-lined, tapered cylinder
Compaction	Not stated (Standard Proctor, ref.3)	Vibrating hammer	Mod. Proctor or Vibration
Max. particle size, mm	Not stated	Not stated	38
Saturation procedure	Compaction at high water content	24 hours with base in water (may change to 5 days)	48 hours soaking procedure, or under vacuum
Water supply level	Constant at base	Constant at base	Variable

TABLE 3.7.2 Summary of Frost Heave Test Conditions (after Gaskin, 1981)



NOTES: Standard tests performed by Cold Regions Research and Engineering Laboratory, specimens 6 in. dia. by 6 in. high, frozen at penetration rate of approximately 0.25 in. per day, with free water at 38°F continuously available at base of specimen. Specimens compacted to 95% or better of applicable standard, except undisturbed clays. Saturations before freezing generally 85% or greater.

* Undisturbed specimen

** Indicated heave rate due to expansion in volume, if all original water in 100% saturated specimen were frozen, with rate of frost penetration 0.25 inch per day.

FIGURE 3.7.1 Range in the Degree of Frost Susceptibility of Soils According to the U.S. Army Corps of Engineers (1965). (after Chamberlain, 1981a)

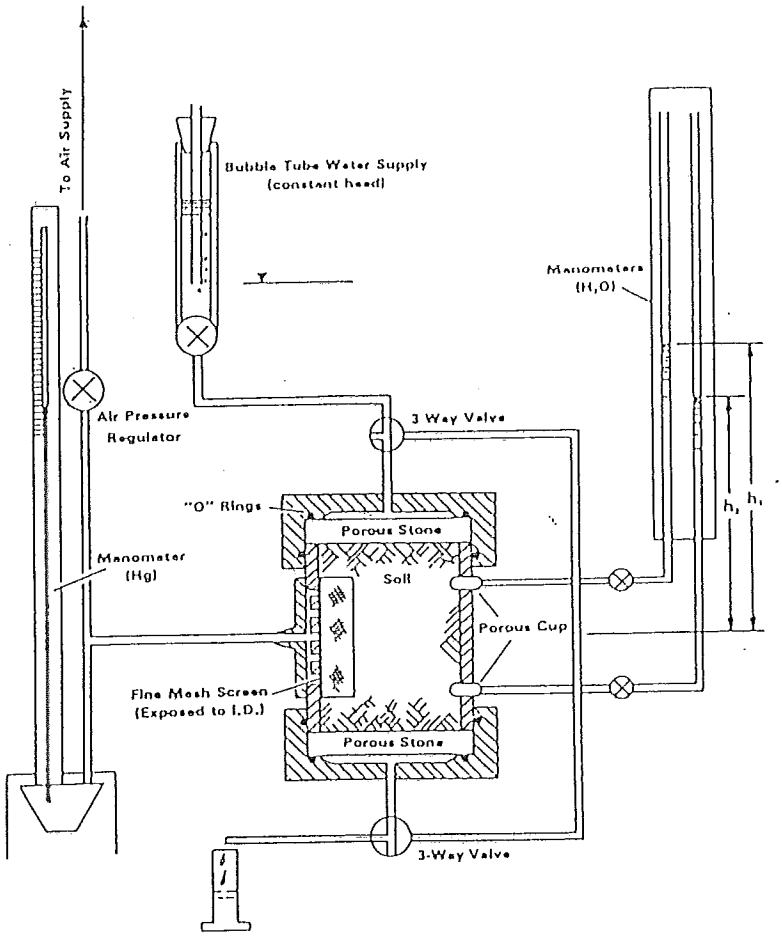


FIGURE 3.7.2 Pressure Cell Permeameter (after Ingersoll, 1981)

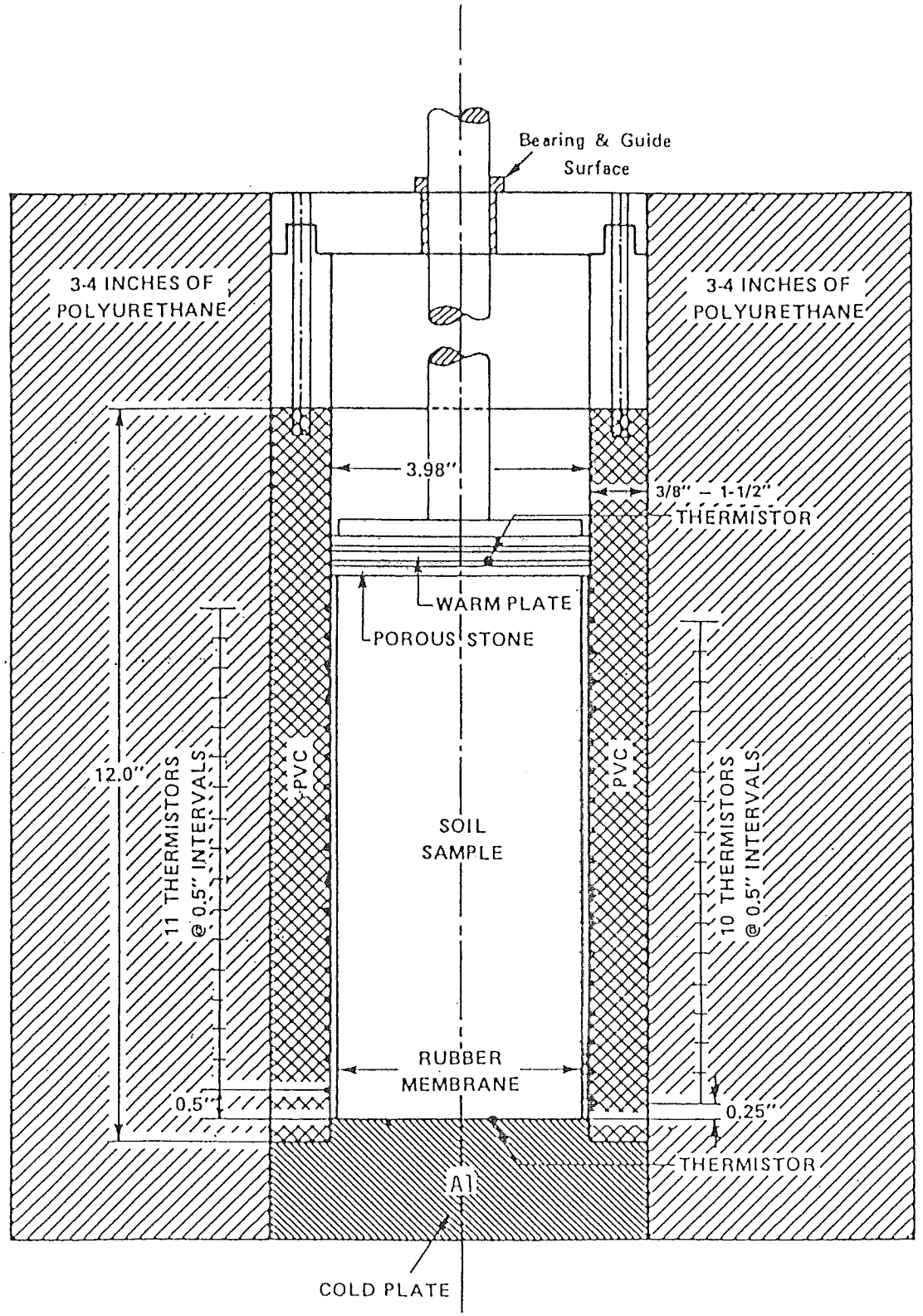


FIGURE 3.7.3 Representative Frost Heave Test Cell
(after Battelle Columbus Laboratories, 1981)

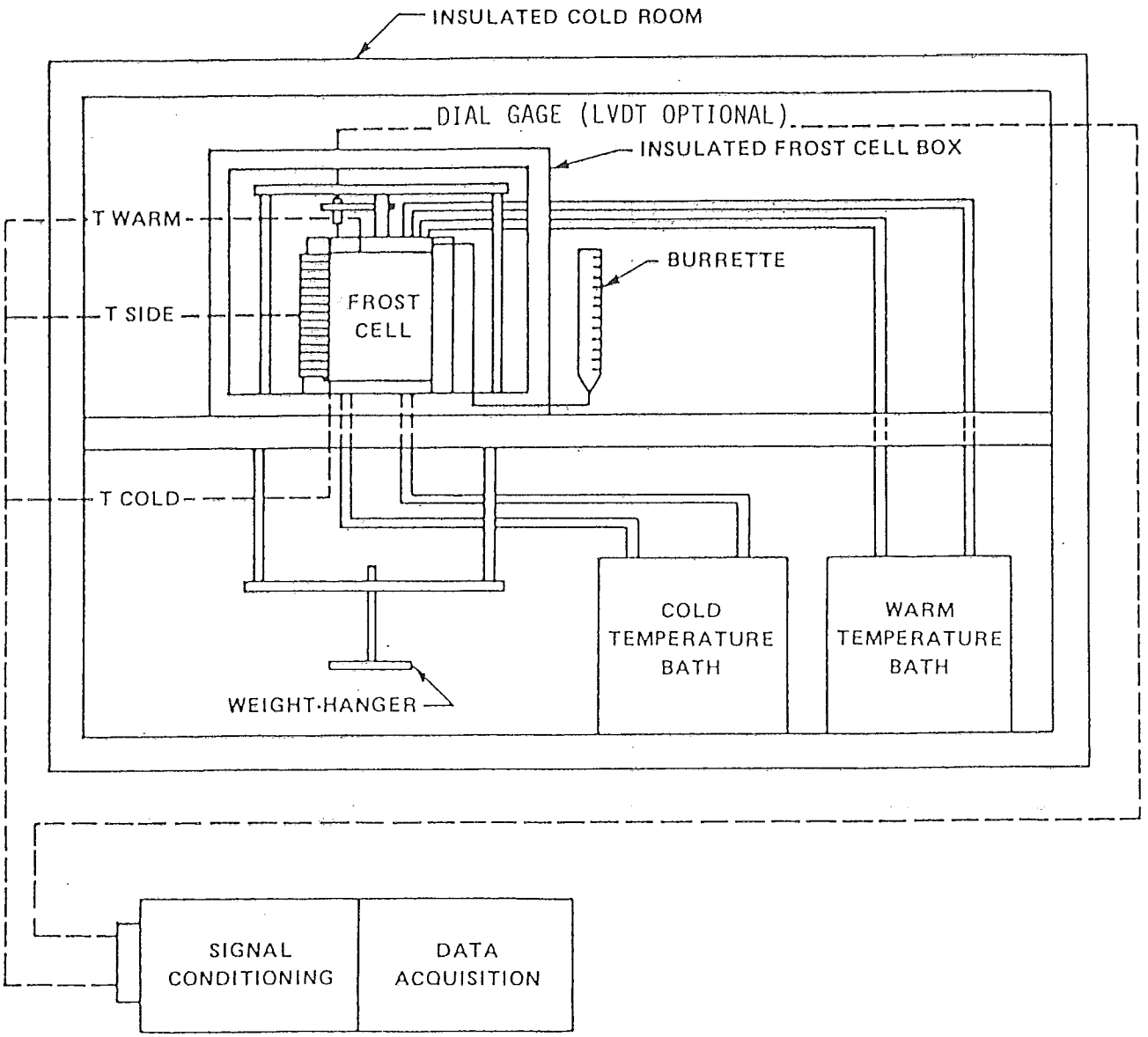


FIGURE 3.7.4 Frost Heave Experimental Set-Up
(after Battelle Columbus Laboratories, 1981)

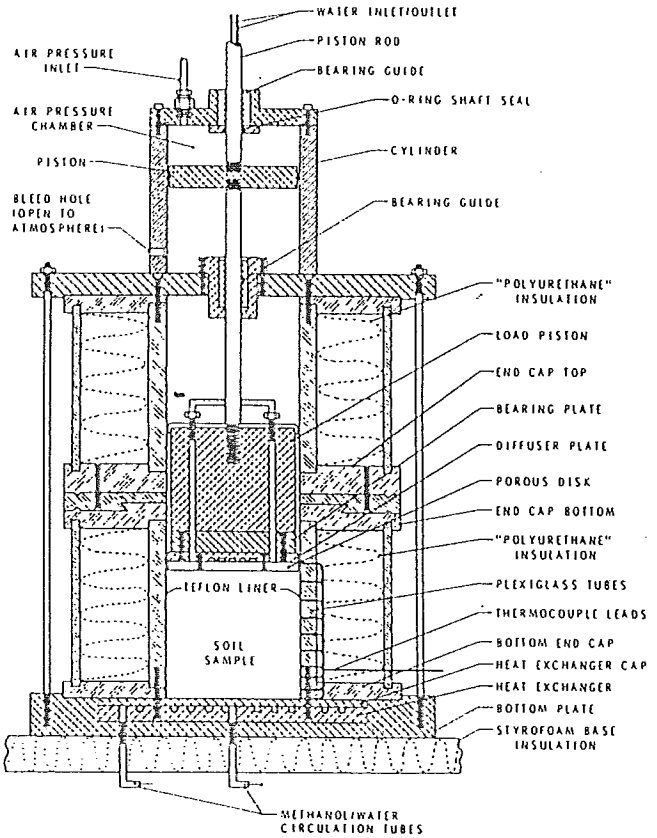


FIGURE 3.7.5 Frost Heave Test Cell
(after Penner and Ueda, 1977)

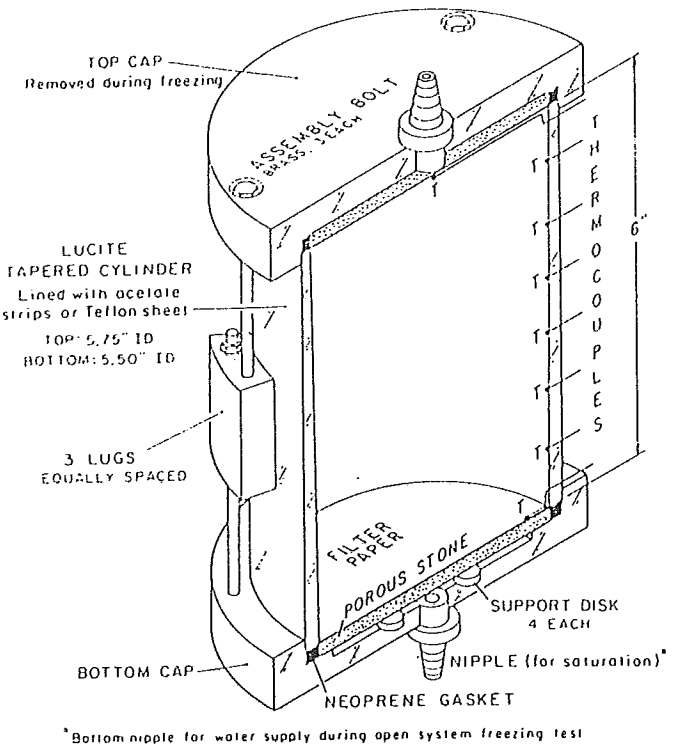


FIGURE 3.7.6 Inside-Tapered Freezing Cell (from Kaplar, 1974)

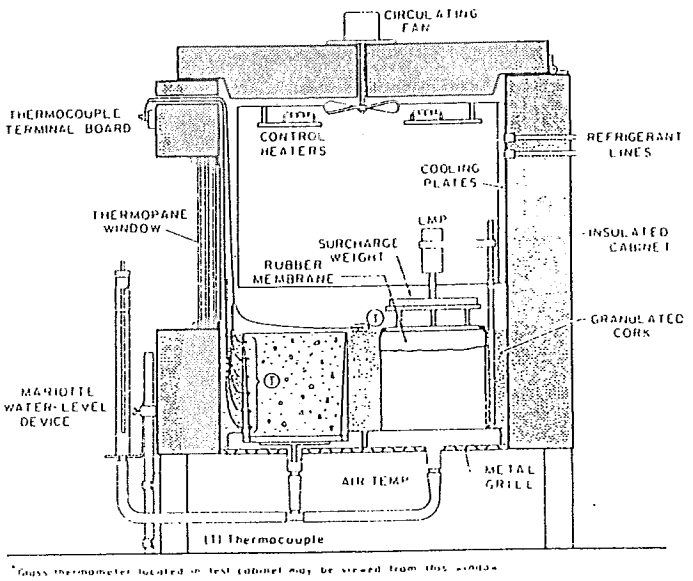


FIGURE 3.7.7 Sketch of Cutaway View of Freezing Cabinet (after Kaplar, 1974)

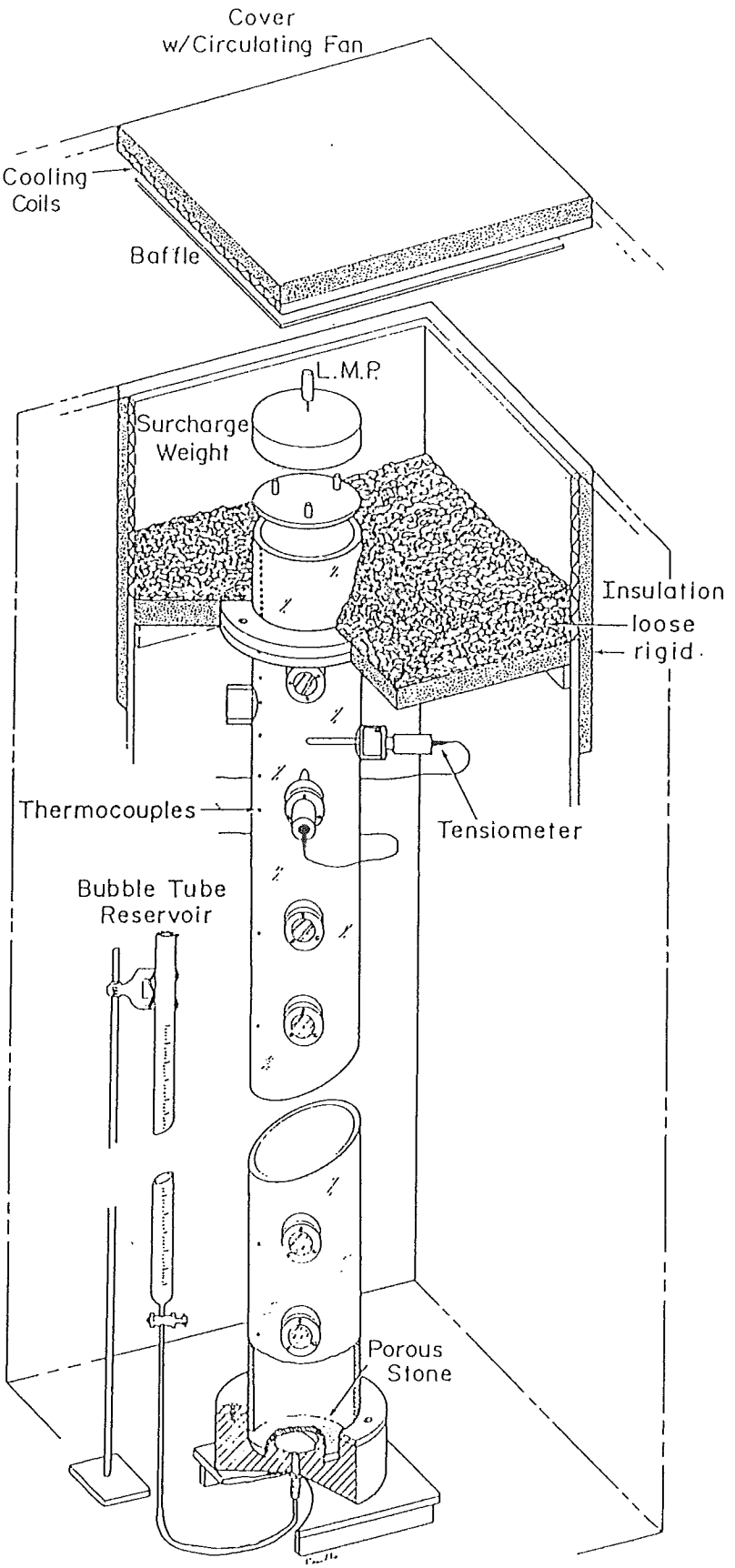


FIGURE 3.7.8 Test Cylinder to Evaluate Effects of Surcharge on Frost Heaving (after Berg, et al, 1980)

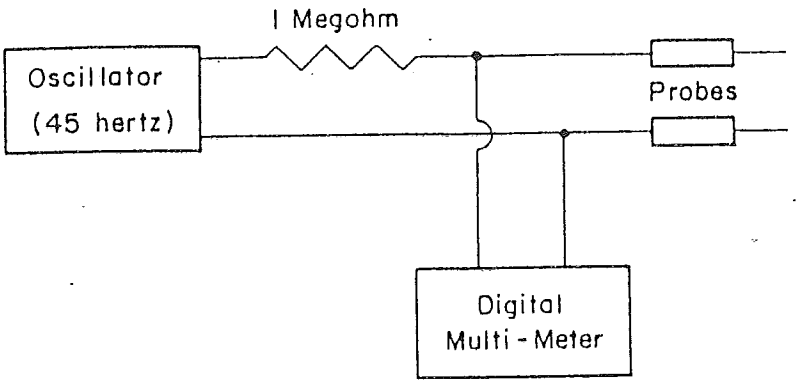


FIGURE 3.7.9 Diagram of A.C. Resistance Probe.
(after Ingersoll and Berg, 1981)

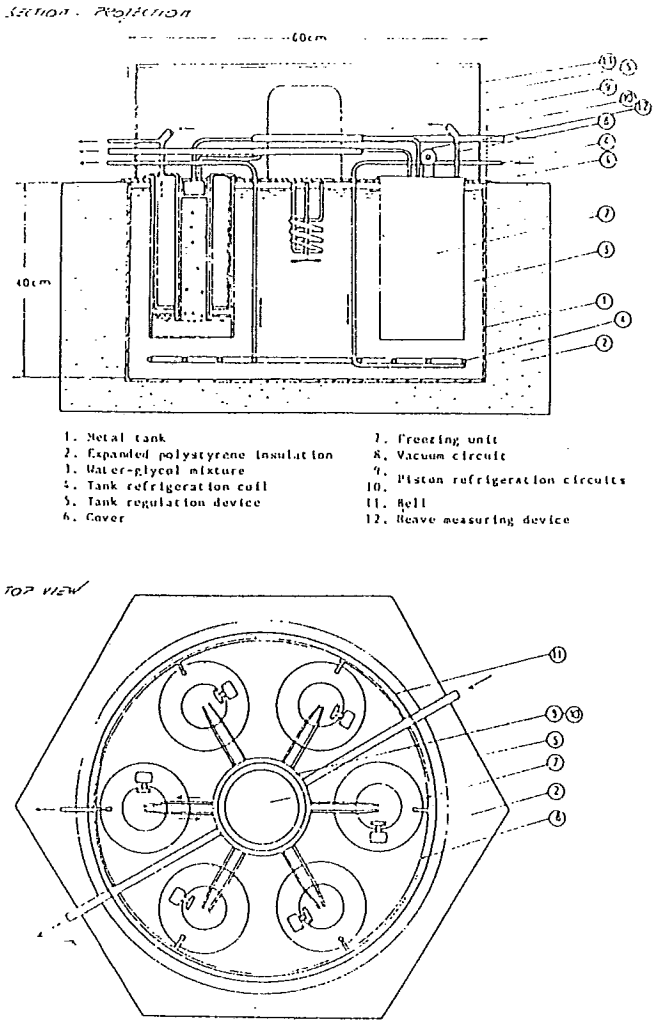


FIGURE 3.7.10 Diagram of Experimental Tank (after Livet, 1981)

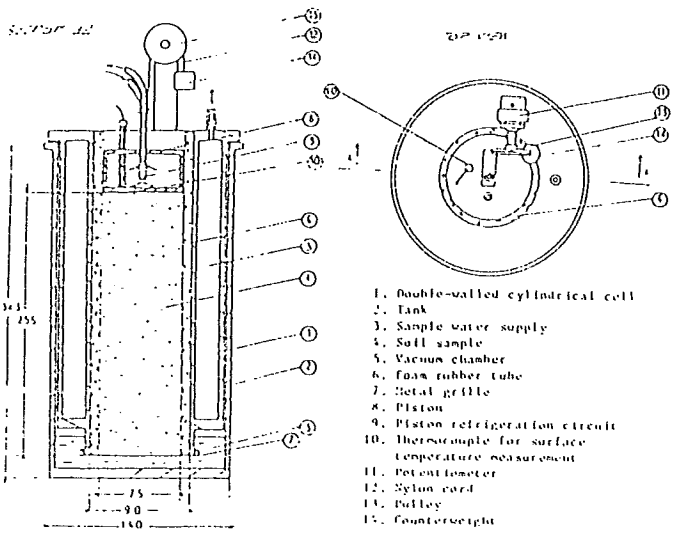


FIGURE 3.7.11 Diagram of Freezing Unit (Dimensions in mm) (after Livet, 1981).

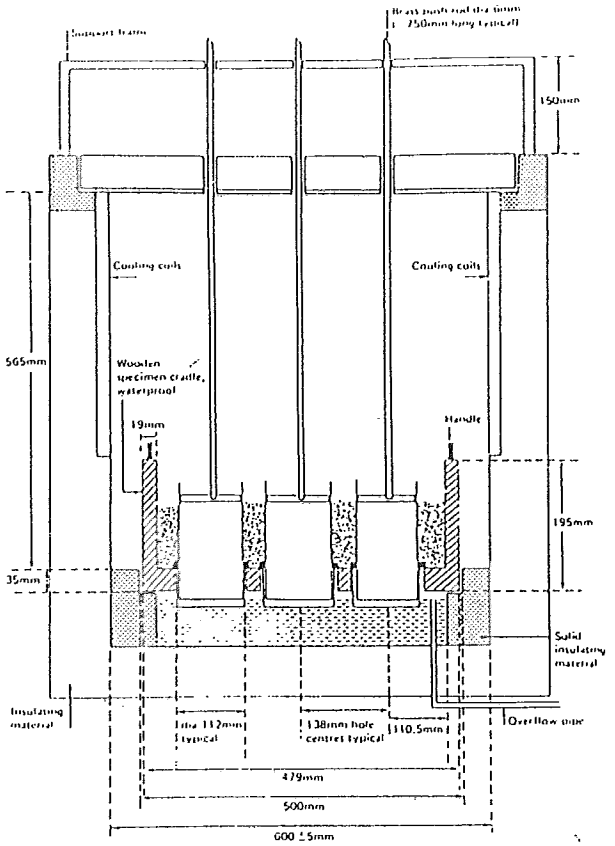


FIGURE 3.7.12 Section Showing Main Features and Dimensions of Test Chamber (after Sherwood, 1981)

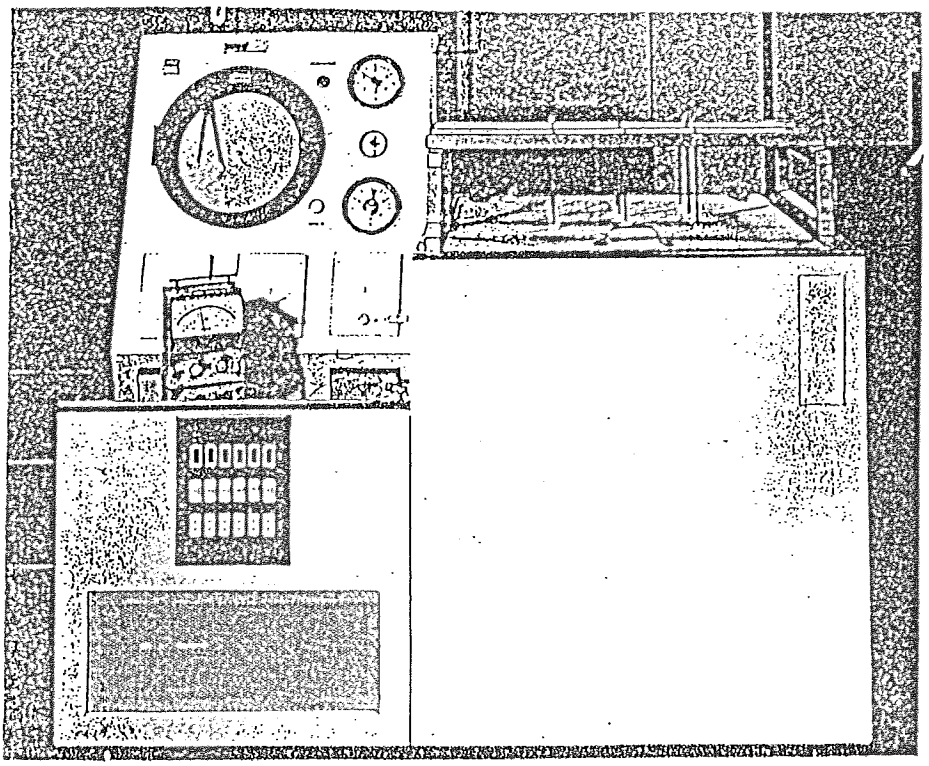


FIGURE 3.7.13 Self-Refrigerated Unit for Carrying out TRRL Frost Heave Test (after Sherwood, 1981)

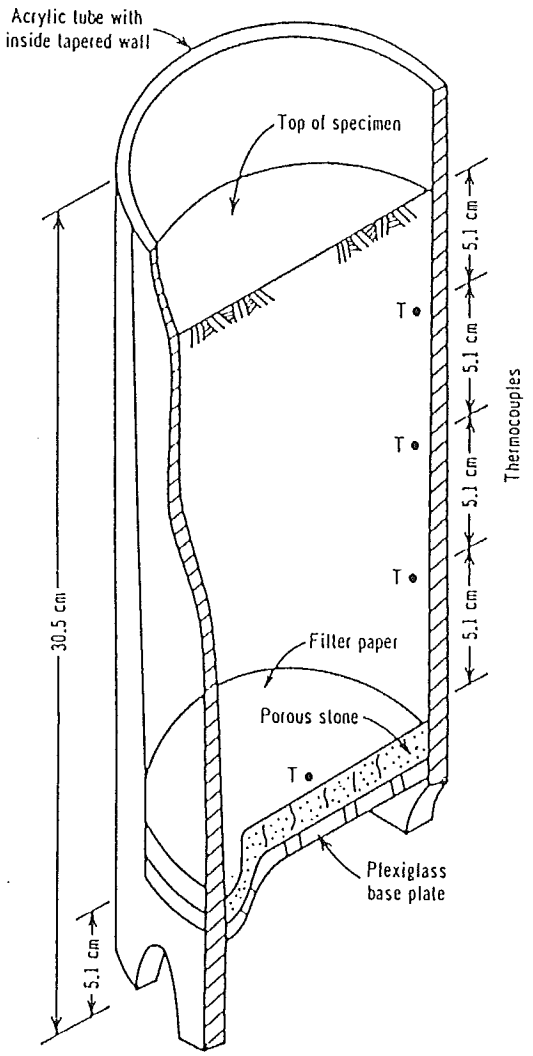


FIGURE 3.7.14 Cross Section of Freezing Cell (after Sherif et al, 1977)

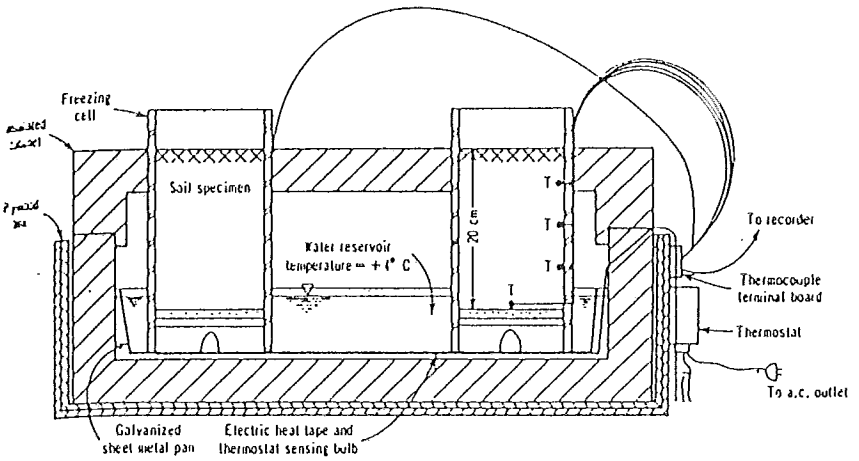


FIGURE 3.7.15 Details of Soil Insulating Cabinet and Water Reservoir (after Sherif et al, 1977)

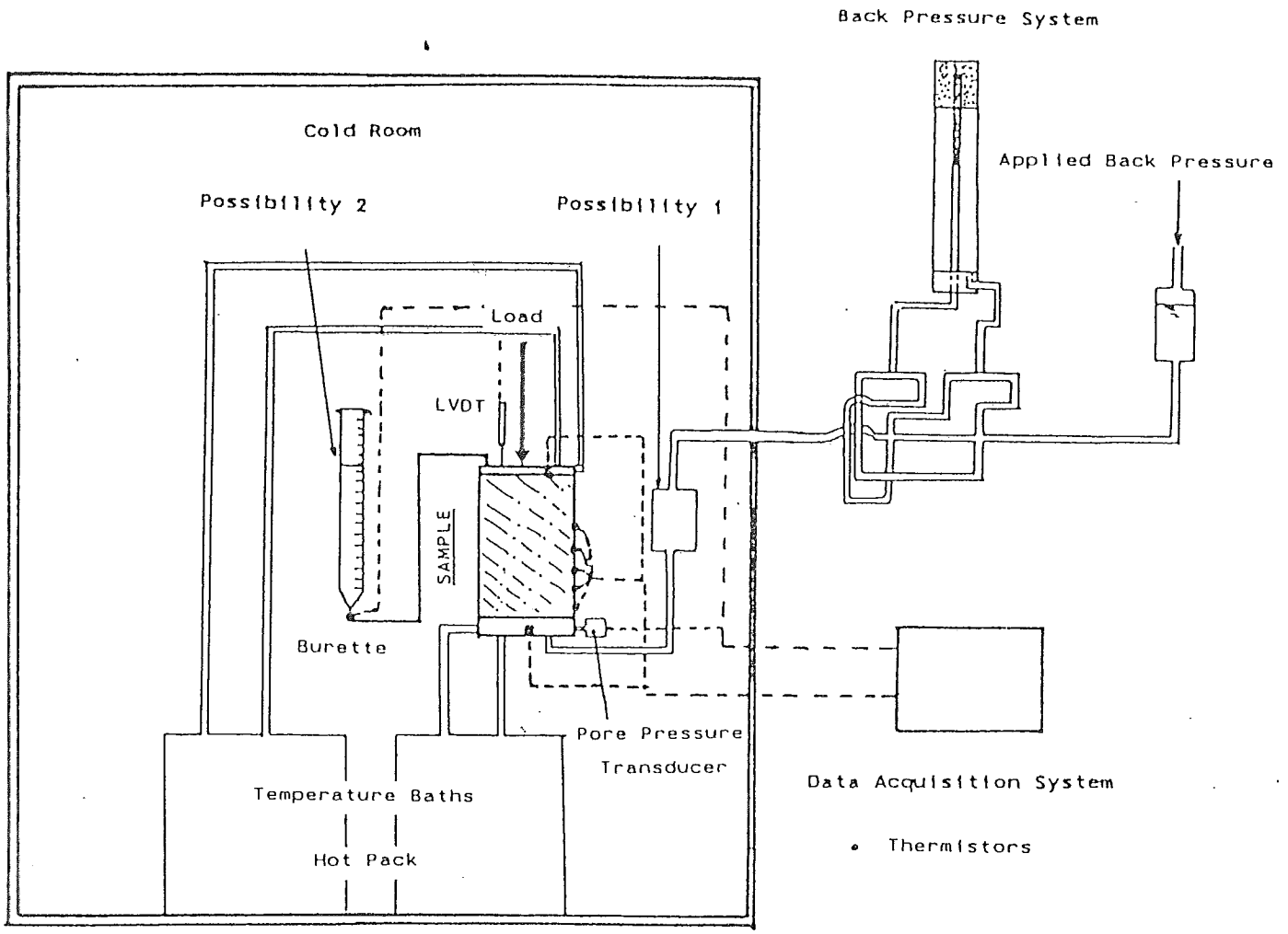


FIGURE 3.7.16 Schematic Diagram of Experimental Apparatus (after Konrad, 1980)

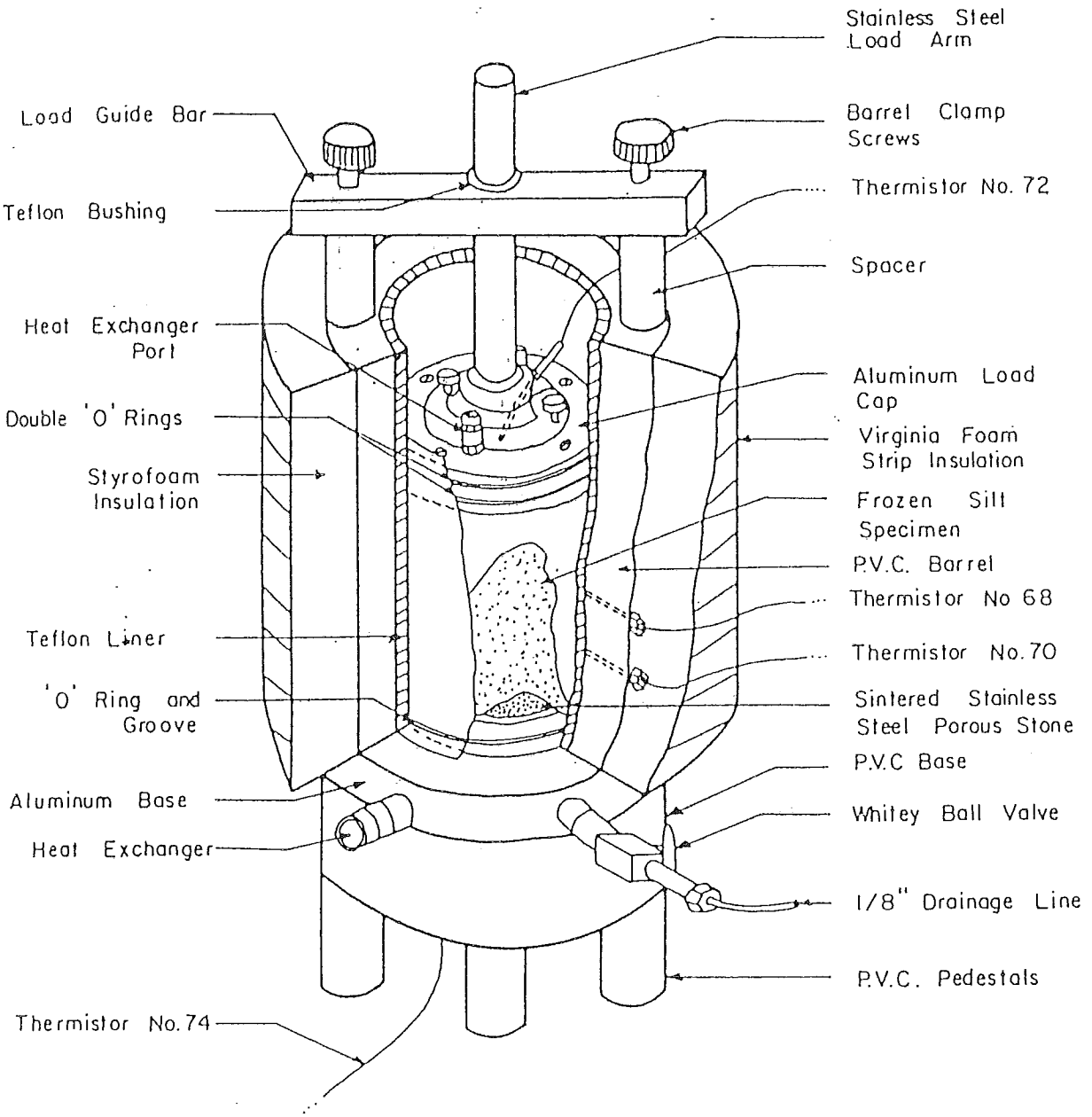
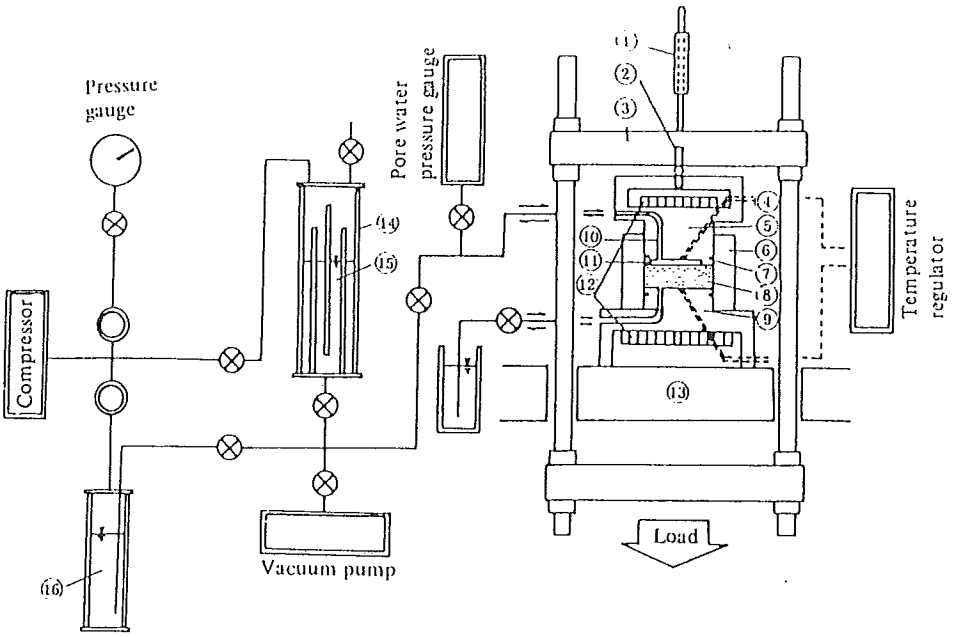


FIGURE 3.7.17 Cutaway View of a Freezing Cell (after Konrad, 1980)



(1) Displacement gauge
(2) Suspending tool
(3) Loading frame
(4) Thermistor
(5) Piston-type cooling plate
(6) Acryl cylinder
(7) O-ring
(8) Specimen
(9) Cooling plate
(10) Pore water outlet opening
(11) Porous metal
(12) Thermomodule
(13) Loading platform
(14) Pressurized container
(15) Capacitance type
(16) High-pressure tank
◎ Pressure adjusting value
⊗ Valve

FIGURE 3.7.18 Apparatus for Frost Heave Test (after Jessberger and Carbee, 1970).

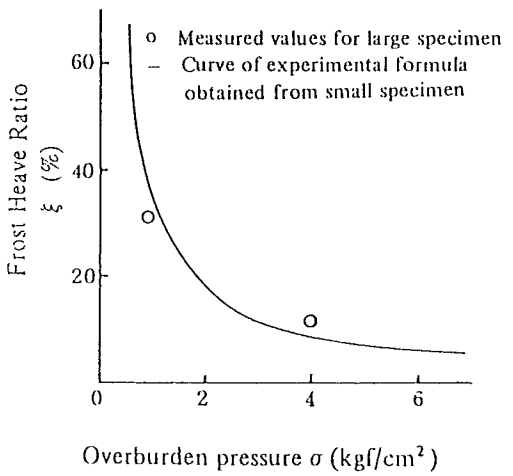


FIGURE 3.7.19 Comparison of Frost Heave Ratio Between Large and Small Specimens (after Jessberger and Carbee, 1970).

3.8 THAW CONSOLIDATION TESTING

3.8.1 General

When thawing occurs in permafrost, water is liberated and pore pressures are generated. The strength of the thawed soil depends on the pore pressure and the settlement rate will vary with pore pressure dissipation. A knowledge of the above conditions is essential to quantitative foundation analysis. Considerable work has been done to understand the thaw consolidation behaviour of different soils. Luscher and Afifi (1973) summarize the generally accepted concepts as follows:

1) Thaw settlement behaviour depends on the amount and distribution of ice in the soil. Ice may occur in frozen soil in distributed form, in lenses and veins, and as massive ice inclusions.

2) For soil with distributed ice only, a gradually advancing thaw front melts the ice. Depending on several factors, including the degree of saturation and the tendency for volume change of the soil skeleton, excess pore water may be generated at the thaw front. This excess water is dissipated according to physical laws similar to those governing consolidation phenomena in thawed soils. Hence, thaw straining may or may not occur and may or may not have a consolidation time lag associated with it.

The thaw strain T is generally believed to be composed of two components:

$$T = A_0 + a_0\sigma$$

in whcih A_0 is a constant for a given soil and a_0 is proportional to the applied stress σ. The constants are determined by thaw consolidation tests.

3) For soil with both distributed ice and ice lenses, it is best to separate the contributions to thaw settlement due to distributed ice and ice lenses. Arching reduces the settlement contribution of a lens to a value less than the lens' thickness. Alternately, thaw consolidation tests could be made on soil samples containing ice lenses, but the samples should have a lateral dimension several times that of the lenses.

4) Settlement due to thawing of massive ice inclusions, including ice wedges, will be very large and irregular and must be evaluated individually.

3.8.2 Thaw Consolidation Testing at the University of Alberta

A general solution to the problem of one-dimensional thaw-consolidation was formulated by Morgenstern and Nixon (1971). Morgenstern and Smith (1973) report on an experimental program designed to test this theory. Subsequently, Nixon (1973) made improvements on the basic apparatus and performed further testing. The basic apparatus developed by Smith is described below plus the improvements by Nixon. Detailed test procedures used by Nixon are then given.

3.8.2.1 Apparatus After Morgenstern and Smith (1973)

A diagram of the apparatus used to perform the thaw-consolidation tests is shown in Fig.3.8.1. The permode (permafrost oedometer) is basically a standard oedometer, wherein settlements can be measured to an accuracy of 0.0001 in. as thaw-consolidation progresses. Drainage is one way to the top and pressure is measured to an acccuracy of 0.003 psi at the bottom of the sample. Temperatures can be measured at the top, bottom, and at two intermediate points on the side of the soil through the use of thermo-couples or thermistors. The temperatures are measured to an accuracy of $0.2^{o}C$ with thermocouples and $0.01^{o}C$ with the thermistors.

The lucite ring of the permode minimizes radial heat flow and is encased in an outer steel jacket which minimizes radial deformation. The inner surface of the ring is surfaced with teflon and is fitted with a rubber membrane as shown. This was done to reduce side friction. Observations of pore pressure response and dissipation on unfrozen soils loaded in the conventional manner indicated that this was successful (Smith, 1972). The load cap is fitted as loosely as possible without allowing extrusion of the soil around it. As shown in the diagram, a frictionless teflon guide is provided to ensure that the load cap travels smoothly downwards without tilting. This arrangement was found to give much better settlement and pore pressure data during testing.

The volume of fluid in the pore pressure measuring system is kept to a minimum in order to make the system as hard as possible.

Freezing of the fluid in the pore pressure measuring system is prevented by the addition of 50% ethylene glycol to the distilled water in the system. The valves, positioned as shown, permit the re-zeroing of the pressure transducer while a test is in progress, without affecting the pressures at the base of the soil. Re-zeroing was found necessary to compensate for changes in atmospheric pressure which occurred during longer consolidation tests.

The temperatures at each end of the sample are controlled through the use of the thermo-electric elements located as shown, one at the base of the permode and one in the load cap. The temperature of these elements can be regulated within an accuracy of $0.2^{o}C$ through the use of temperature controllers. The power output of the controller is regulated by a thermisotr sensor through a feedback system. The sensor is placed at the point where temperature is to be controlled and the specific temperature can be established by adjusting the potentiometer to the applicable resistance. It was found helpful to regulate the input voltage to the controller through the use of a Variac, in order to limit the current applied to the thermoelectric elements.

An adequate heat sink is provided for the lower thermoelectric element by placing it directly on a thin flat plate which is cooled by a refrigeration unit. During freezing of the sample a heat sink is provided for the top element by packing the top of the load cap with dry ice. It was found that the presence of air at room temperature around the top of the load cap during thawing of the sample provided a sufficient heat source for the top thermoelectric element.

An overall schematic diagram of the test configuration is shown in Fig.3.8.2. The sample was loaded directly through a counterbalanced load hanger. It was found that due to the large strains involved in testing frozen soils it was extremely difficult to maintain a constant load on the sample when levered loading systems were used, since the lever arm had to be continuously balanced. A constant applied load is necessary in order to obtain accurate pore pressure data. The chief disadvantage of the direct loading system is that the magnitude of the applied loads is limited.

Vertical displacements are read directly with the dial gauge or can be recorded on the digital recorder through the use of an LVDT. Temperatures are recorded at 2 min intervals on the strip chart recorder and pressures, as measured by the transducer, are read with a strain gauge bridge and multiplied by the appropriate calibration factor.

3.8.2.2 After Nixon (1973)

(i) Apparatus

It was necessary to design and fabricate an apparatus capable of satisfying the stress and thermal boundary conditions involved in a thaw-consolidation test. The apparatus developed by Smith (1972) was shown to meet these requirements in a satisfactory manner when testing remolded soils. However, based on experience obtained from a large number of tests, and anticipating the extra complexities in testing undisturbed samples, Smith (1972) gave recommendations for improvements to the original apparatus design. The design of the thaw-consolidation apparatus was subsequently altered to allow the testing of undisturbed samples by making the following changes.

1) the pore pressure measuring system at the base of the apparatus was redesigned to permit flushing of the measuring system;

2) provision was made to measure deflections directly from the ring of the oedometer to the loading plunger; and

3) the apparatus was also made so that frozen samples were mounted on the base plate and a split oedometer ring clamped around the sample.

This latter innovation facilitated the placement of a frozen sample in the apparatus, which was not possible previously.

A diagram of the improved apparatus is given in Fig.3.8.3. Except for the improvements listed above, the same features were incorporated in the oedometer described by Morgenstern and Smith (1973).

(ii) Procedure

The extensive laboratory testing carried out by Smith (1972) demonstrated very good agreement between theoretical predictions and the observed behaviour of remoulded soils. However, it is obviously desirable to extend this work by testing undisturbed natural samples of permafrost. It is extremely important to investigate the effects of the natural structure of permafrost on the predictions provided by the thaw-consolidation theory, and therefore determine the applicability of the theory to field problems.

With the design improvements incorporated in the apparatus described in the previous section, it is now possible to place a frozen sample of the correct dimensions in the apparatus, and carry out a thaw-consolidation test.

Samples of frozen core approximately 3 1/2 inches in diameter were obtained from Norman Wells, N.W.T. and from Noell Lake, northeast of Inuvik, N.W.T. The core was inspected visually, and samples were selected for testing.

The samples were prepared in a large 'walk-in' cold room by first cutting a rough section of core to approximately 2 1/2 inches in length. The frozen soil was then clamped in a milling machine which was fitted with a specially constructed cutting tool. This cutting device was fabricated from a three inch long section of thin-walled steel tubing having an internal diameter of approximately 2.65 inches. The cutting edge of the cylinder was formed by bending the lip of the cylinder inwards and then matching the lip to a sharp edge. The internal diameter of the lip was machined to 2.5 inches exactly, and when mounted in the milling machine, the cylinder formed an effective device for cutting samples 2.5 inches in diameter for testing in the oedometer. With the cutting tool rotating at about 300 rpm, it was forded into the frozen core at a rate of 0.2 inches per minute. The cutting action produced a minute amount of melting at the cylindrical surface of the sample, but the effects were estimated to penetrate less than 1 mm into the sample. After the cutting tool had penetrated approximately two inches, it was withdrawn. The thawed 'skin' around the sample was observed to refreeze almost instantly. The sample was removed from the milling machine, and the ends were trimmed square on a band saw. The dimensions of the sample were carefully measured, and the sample weighed on a balance to 0.01 g. These data were used to calculate the frozen bulk density. The sample was quickly sealed in a plastic bag to prevent sublimation of the ice, and stored for later use. Trimmings and end cuttings from the sample preparation were used to obtain the initial moisture content of the frozen soil. Two reconstituted samples of Mountain River clay and Devon silt were also prepared to ascertain if the thaw-consolidated apparatus was functioning correctly.

The sample was set up in the apparatus by first allowing the component parts of the apparatus to come to the temperature of the room at which the test was being carried out. As stated previously, the pore pressure measuring system and porous stone were saturated with ethylene glycol. A meniscus of glycol was maintained on top of the porous stone, and a wet filter paper was carefully placed on the glycol, and the frozen sample lowered gently onto the filter paper. The weight of the sample on the porous stone and base plate squeezed out all excess glycol, and a rubber membrane was placed around the sample. The membrane was sealed to the base plate by a rubber O-ring seal. The two sections of the split barrel were clamped around the sample, and then the barrel was bolted to the base plate. The membrane was then held at the top of the barrel, and the load cap assembly was

pushed down the barrel to make contact with the soil sample. The overburden loading was then placed on the load hanger which was brought in contact with the load plunger. The vertical dial gauge was brought to bear on the load cap, and the initial reading was adjusted to equal the height of the sample. As the dial gauge had a 2 inch travel, this permitted the direct reading of sample height at any stage of the test. Any extraneous pore pressures in the measuring system were allowed to dissipate and the pore pressure measuring system was closed from the atmosphere. The assembled sample and apparatus were then left undisturbed for approximately four hours to allow the temperatures, height and pore pressure readings to become constant.

After applying a step increase in surface temperature to the sample, pore pressures, settlements and temperatures were recorded at one minute intervals until thawing and settlement were complete.

3.8.3 Thaw Consolidation Testing by Woodward-Lundgren and Associates

3.8.3.1 After Smith et al (1973)

As part of a program to evaluate the thaw-consolidation properties of permafrost at great depths a study was performed to estimate the significance of sample disturbance effects on laboratory data. Uniaxial thaw-consolidation tests were performed on both recovered permafrost cores and artificially frozen specimens using the uniaxial consolidation cell shown in Fig.3.8.4. The test procedure is given below (after Smith et al, 1973):

There were no generally accepted standard test procedures for thaw-consolidation testing of frozen soils; however, extensive work with frozen soils in the Soviet Union had resulted in recommended procedures. Their suggested criteria and test procedures were used, when applicable, to perform the uniaxial thaw-consolidation tests described in the following paragraphs.

The prepared samples were placed on the testing frame, and a small seating load was applied for approximately 5 sec. The height of the uniaxial sample was recorded and the load applied to the frozen sample. The frozen samples were brought back approximately to their in situ temperature and axial stress

level and allowed to come to equilibrium at that condition. In all cases it required at least 24 hours to reach an equilibrium state.

This equilibrium was established from a Soviet criterion for sand permafrost when the deformation rate is less than 33.0×10^{-5} cm/h for specimens 2-3 cm in height. Deformation rates prior to thawing the frozen sand samples ranged from 5.1 to 23.4×10^{-5} cm/h. Therefore, all the frozen samples reached equilibrium within 24 hours.

The frozen samples were then allowed to thaw gradually under the same axial stress. During the uniaxial thawing, the loading piston was allowed to warm while the cooling coils were maintained below freezing. This procedure combined with the thermal properties of the lucite cells ensured slow uniaxial thawing of the samples from the top to the bottom.

At the completion of each thaw-consolidation test, the filter paper placed on top of the thaw-consolidation specimen was examined for evidence of the possible extrusion of grease that was used to fill the annular space between the sample and the consolidometer wall. In every case, no evidence of grease extrusion was present. Therefore, minor errors in the axial strains calculated from changes in specimen heights due to extrusion of the side wall lubricant were effectively eliminated with the test apparatus used.

Because of the high pressures and changes in temperature occurring during a thaw-consolidation test, it was necessary to calibrate the effect of load and temperature changes on the axial deformation measurement. The load and temperture calibrations were used to account for the expansion and contraction in the test equipment. All axial deformation measurements were corrected to reflect only specimen deformations.

3.8.3.2 After Luscher and Afifi (1973)

In connection with a project in Alaska, thaw-consolidation tests were run on a large number of natural permafrost samples to establish parametric relationships between thaw strain and frozen soil index properties. The tests included conventional uniaxial thaw consolidation tests with standard consolidation test equipment as well as triaxial consolidation in a triaxial cell. The triaxial tests were utilized for granular soils to overcome frictional problems. In the triaxial tests,

both isotropic and anisotropic loading conditions were used. Ratios of vertical to horizontal stresses were used such that essentially one-dimensional deformation occurred. Procedures for the uniaxial tests (in a consolidation cell) and anisotropic tests (in a triaxial cell), are given below:

(i) Uniaxial Thaw Consolidation Tests

The samples used in these tests have a diameter of about 5 cm and a height of 2 - 4 cm. Drainage during the test is through filter papers and porous disks placed at the top and bottom of the samples. These tests are made using a standard oedometer device.

The tests on silts consist of two major steps - thawing and consolidation under one pressure and further consolidation under additional pressures. First, the frozen sample is placed in the consolidation unit in the cold room, quickly brought to the laboratory, loaded with a vertical pressure, and left to thaw and consolidate for 24 hours. The changes in sample height are recorded during this period. Next, the sample is consolidated with additional pressures. Six different pressure sequences, defined by kilonewtons per meter squared, are used to consolidate groups of six samples:

12	24	48	96	192	384
	24	48	96	192	384
		48	96	192	384
			96	192	384
				192	384
					384

The first number in each of these sequences represents the thaw pressure, and the remaining numbers represent pressure reached after thaw. All tests on silt-sands are made with a single pressure of 96 kN/m^2.

The uniaxial thaw consolidation test is suitable for clays, silts, and sands, where meaningful tests can be made on samples of relatively small diameter and small height. To use this test for gravel, relatively large-diameter samples would be required. Also, trimming samples to closely fit the consolidation mold is almost impossible for coarse-grained soils.

(ii) Anisotropic Thaw Consolidation Tests

The anisotropic thaw consolidation test has been devised to overcome the difficulties of the uniaxial thaw consolidation test for coarse-grained soils. In this test, the standard triaxial equipment (with some modification) is used. Samples have a diameter of 4 - 8 cm and a height-to-diameter ratio of 2:2.5.

In principle, a sample can be caused to consolidate purely unidimensionally (K_0 condition), either by using a confinement ring (in the standard consolidation tests) or by applying principal stresses that have a certain proportion to each other (in the triaxial test). Experience has shown that the ratio of K_0 of lateral stress ($\sigma_2 = \sigma_3$) to axial stress (σ_1) leading to deformation in the direction of σ_1 only ranges from 0.35 to 0.50 for granular soils. These K_0 values correspond to a principal stress ratio (σ_1/σ_3) ranging from 2 to 3. Elastic theory, using values of Poisson's ratio of 1/3 to 1/4, leads to the same result.

The data obtained in this investigation, using anisotropic thaw consolidation for silt-sands, confirm these concepts. Similar behaviour is expected for gravel samples that are statistically homogeneous. For practical purposes, gravel samples with a ratio of particle size to diameter of 1/3 or less were considered statistically homogeneous and were tested using this technique.

At the beginning of this investigation, all samples are loaded in the frozen condition and are kept frozen using refrigeration coils that surround the consolidation ring. The strains in the frozen condition obtained within 24 hours are found to be insignificant, compared with the strains experienced during thaw. For this reason, the initial step of maintaining the sample frozen for 24 hours under the applied load is omitted and all tests are made by allowing samples to thaw under a selected load as described for the uniaxial thaw consolidation test.

3.8.4 Thaw Consolidation Testing at CRREL (After Crory,1973)

Crory (1973) notes that the thawing of permafrost can produce a wide range of volume changes, since the ice volume in situ can vary significantly with depth and horizontal distances. Consequently the resultant settlement can be quite variable. Crory's work was directed to the development of practical methods of determining the settlement of perma-

frost of thawing using common laboratory tests and simple relationships. The laboratory tests program is described as follows:

Thaw-consolidation tests conducted at USA CRREL to date have concentrated on the development of standard test procedures and a thorough understanding of the mechanics involved both in thawing and consolidating or in thawing and expanding. While controlled thawing has been used in the study of shear strength of soils at the thawed-frozen soil interface, the thaw-consolidation tests to date have been conducted with no attempt to control the rate and direction of thawing, on the assumption that the proposed standard tests could best be accomplished in the standard consolidation apparatus. If the distribution of ice in frozen samples was always homogeneous, thermal controls could be designed to produce a horizontal thaw plane in the sample, as depicted in Fig.3.8.5a. Since the ice distribution is seldom uniform, some uneven thawing is inevitable and the thaw front configuration might resemble that shown in Fig.3.8.5b. The inaccuracies in remotely measuring the advance of the thaw front with time were a serious handicap in computing the unit strain within the shallow thawing depths, so simple flooding of the device with room temperature de-aired water and initiation of all-around thawing was elected as the test procedure. With all-around thawing, the inner portion of the sample is the last to thaw (Fig.3.8.5c), and consolidation reflects the thawing of the inner core rather than the entire sample. recognizing this, no real use is made of any of the data taken during the thawing process. Only the strain at the end of thawing is utilized. Normally, a seating load of 6.18 or 12.25 kN/m^2 is applied during the thawing period. After the sample has completely thawed and no further volume changes are observed, the sample is loaded in the conventional manner employed in testing thawed samples.

3.8.5 Thaw Consolidation Tests by Woodward-Clyde and Associates (1971)

(i) General

The triaxial test allows the most versatility in thaw-consolidation testing. The triaxial sample may be subjected to a single isotropic stress state or any combination of prescribed deviator stresses and thawed isometrically, with or without free drainage; whereas the uniaxial sample may only be subjected to a prescribed axial stress and thawed uniaxially with free drainage. However, the uniaxial test procedure is simple and well accepted. Many small samples can be tested simultaneously with the test apparatus to define the approximate range of behaviour of the soil during thawing under different pressures. For these reasons the uniaxial test is probably more widely used than the less well

understood slightly more complicated triaxial test which also requires a larger sample. The general test procedures are the same for both tests.

Careful consideration should be given to which, if either of these tests adequately models a given design condition. The uniaxial test is probably more appropriate for large shallow foundations where edge effects may not be significant and where water is probably going to drain towards the loaded warm surface. In contrast, deep foundations where the direction of thawing and drainage is subject to question, are probably more accurately modelled by the triaxial test. Neither of the tests are felt to provide data of a sufficient degree of accuracy that settlement rates can be predicted. Actual settlement rates will probably be governed by either the permeability of the soil, or the rate of thawing, or a complex combination of these factors. The laboratory tests cannot accurately model these rate related conditions though they may provide guidance in estimating the total amounts of settlements which can be expected.

(ii) Test Procedures

The uniaxial consolidometers are brought into the laboratory and placed in position on the testing frames, after preparation in the cold room. The coolant lines are immediately connected to maintain the sample in the frozen state. Dial gauges are then zeroed and a seating load equal to the calculated overburden is applied to the sample for a period of approximately five seconds. The initial dial reading measuring the height of the seated uniaxial sample is recorded and the first load increment is then applied to the frozen sample. Because of the small size of the sample and the need for very accurate measurements this seating procedure is desirable to ensure a press fit of the sample in the consolidometer, as well as firm contact between all components. For partially saturated samples some sample compression no doubt occurs during this seating period. In view of the relative magnitude of consolidation which occurs on thawing this small amount of precompression is probably not significant for most soils. The magnitude of the first load increment is usually selected equal to the design foundation pressure plus the approximate overburden pressure based on the depth from which the sample was recovered and the unit weight of the overlying soils in the profile. The temperature at which the sample is brought to equilibrium is selected to represent the existing mean annual soil temperature expected or measured (below a depth of 10 M) at the site. Thus the frozen samples are brought back to their approximate in situ temperature and pressure. When a series of tests is conducted on samples from the same depth, the magnitude of the first pressure increment is changed so that its effect on

the consolidation curve in the frozen state and during thawing can be determined. The first pressure increment is applied to the sample for a period of at least 24 hours. The same equilibrium criteria are used for this test as were described for the unconfined compression and triaxial shear tests (Section 3.3.b). The still frozen test sample is then allowed to thaw uniaxially under the same pressure. All samples are allowed to thaw and drain for 24 hours at which time most samples have come to equilibrium under the stress and the air temperature in the laboratory (approximately 20°C). Some heavy clays may require more than 24 hours to equilibrate. During the remainder of the test the thawed samples are treated with standard consolidation procedures. The pressure is increased in increments, and maintained for a period sufficient to allow drainage. Each pressure increment is maintained for one hour in sands and 24 hours in silts and clays. After completion of consolidation in the thawed state, the samples are removed from the consolidometer for a final water content determination.

The triaxial thaw-consolidation tests are run with the same basic procedures as the uniaxial thaw-consolidation tests. After preparation in the cold room the triaxial cell is brought into the laboratory and quickly connected to the cooling system. The volume measuring apparatus, including the cell, transfer lines and manometer, are then de-aired under vacuum to eliminate compressible gas from the system. A small deviator stress is applied to firmly seat the top cap on the sample. The initial dial reading, measuring axial height, and the initial volume reading, measuring the volume of oil in the triaxial cell, are taken. Generally, when a deviator stress is not specified during thawing, the first and all subsequent pressure increments are applied to the frozen sample by increasing the cell pressure while maintinaing a constant principal stress ratio of 1.05. This slight increase in provides sufficient pressure to overcome friction and ensure sample tracking by the dial gauge. This procedure subjects the triaxial sample to an increasing approximately isotropic stress state. The remainder of the triaxial consolidation test procedure, during and after thawing, is identical to that of the uniaxial consolidation test procedure described above.

3.8.6 Thaw Consolidation Testing by Shannon and Wilson Consultants

Recently, a very detailed and complete thaw-consolidation test procedure has been developed in conjunction with pipeline construction in Alaska. This document is included in its complete form herein with the permission of the Northwest Alaskan Pipeline Company, on whose behalf the test procedure was prepared by Shannon and Wilson Consultants.

(i) General

This test shall be used for determining the total settlement of an undisturbed frozen soil sample which is subjected to a two phase load-settlement test. This test may also be referred to as a Uniaxial Thaw Consolidation Test or a Uniaxial Thaw Strain Test.

The first phase of this test shall consist of determining the percent thaw strain of a sample which is loaded and allowed to thaw at room temperature. The second phase consists of determining the percent consolidation of the sample loaded to twice the initial load and allowed to consolidate.

The loading values for this test shall be as follows:

Load 1 = 1,000 psf

Load 2 = 2,000 psf

These loads shall be utilized for all tests unless different loads are specified on the Sample Testing Schedule.

The following is a description of the equipment and testing procedure to be used for conducting this test. Other methods will only be used after approval has been obtained.

(ii) Equipment

A diagram of the test equipment and a list of available cell sizes are presented on Fig. 3.8.6 in this section. The equipment consists of a split lexan cylinder and a load frame or a standard consolidation frame (not pictured). The base and top cap are made of lexan and are fitted with porous stones or discs and drainage lines to allow free drainage of water from the bottom and top of the sample during thaw. O-rings placed around the top cap and base provide seals to prevent moisture from leaking from the cell.

A load is applied by means of a weight hanger assembly or by using a consolidation frame with a 10:1 loading ratio. The load is transferred to the sample through the load ram and top cap. The amount of settlement due to thaw and post thaw consolidation is measured by a dial caliper or dial gauge attached to the load ram.

A set screw through the guide bar is used for confining the load ram to prevent rebound of the sample while it is unloaded during weighing activities between loads.

(iii) Sample Preparation

Samples will be prepared in a controlled manner which limits testing errors due to poor seating such as voids between the sample and loading (top) cap or between the sample and confining cylinder. These errors cannot be eliminated but all precautions will be taken to limit these to an absolute maximum of two percent or less of the total thaw strain.

Two methods of sample preparation will be used depending on the type and condition of the sample. All preparation will be done in a cold room (20°F) to prevent melting of the sample.

If core samples are used, the sample will be cut to a length of approximately 4 to 6 inches by means of a diamond rock saw or a band saw. The specimen will then be placed in a lathe where it will slowly be trimmed to a diameter matching the inside diameter of a cell.

If brass liner samples are used, the sample shall be extruded from the liner. The top and bottom of the sample shall be trimmed flat with a diamond rock saw or a band saw to a length of approximately 4 to 6 inches. The sides of the specimen should be smooth enough so that trimming with the lathe would not be required.

Rock or gravelly samples cannot be lathed, therefore the control on voids is limited on these material types; corrected values will be calculated.

(iv) Procedure

After the sample has been trimmed, it will be weighed and measured and these data used to calculate frozen water content and density. The sample shall then be placed in the cell with the closest diameter, the difference in diameters not to exceed 0.15 inches. If the difference between the diameter of the sample and the closest sized cell is greater than 0.15 inches, the client shall be notified and the test shall not be run unless authorized by the client. After the sample is placed in the cell, the sample and cell are weighed, the top cap is placed on the sample, and the remaining parts are assembled. The dial caliper shall then be attached to the load ram and an initial reading recorded, or if using a dial gauge, the gauge shall be zeroed.

The sample will be loaded to Load 1 pressure (1,000 psf) and allowed to thaw at room temperature. The sample will be kept at Load 1 for approximately 24 hours or until the sample stops settling as observed from the plots. Dial readings will be recorded periodically and plotted on semi-log graph paper (settlement versus log time). The amount of settlement occurring under Load 1 will be used to determine percent thaw strain.

Any change in height observed at the 0.1 minute reading will be considered a seating load or adjustment and that value will be subtracted from the total change in height recorded for Load 1. Seating loads are common and are usually the result of readjustment of the sample within the cell. It is not expected that this initial settlement reflects thaw settlement as the sample has not yet had time to thaw.

It is emphasized that the sample will be kept at Load 1 until the sample is completely thawed and has stopped straining due to thaw consolidation. Sufficient time will be allowed to eliminate remnant frozen zones or zones of only partial consolidation must not exist in the sample before Load 2 is applied.

For this reason, the sample will be kept at Load 1 (without increase to Load 2) until the incremental thaw strain due to extrapolation of the sample strain (settlement) versus log time curve predicts an insignificant increase in strain; say, one percent or less thaw strain. The 24 hour criterion is expected to be generally more than adequate; however, it will not over-ride the settlement rate (incremental thaw strain) criterion.

Once thaw settlement is complete the set screw is applied to hold the load ram and sample in place. The weight hanger or level arm is then removed and the sample is weighed in the cell for calculating dry unit weight after Load 1. After the sample has been weighed, it will be reloaded to Load 1 and the set screw released. Using the set screw should eliminate rebound or seating load adjustments between loads.

An initial dial reading will be recorded, then Load 2 (2,000 psf) will be applied and the sample consolidated. Dial readings shall be taken periodically and plotted on semi-log graph paper. The sample shall be kept at Load 2 for approximately 24 hours or until the slope of the reading-log time plot flattens indicating that primary consolidation has taken place.

The dial readings (time-settlement readings) for each load shall be recorded at periodic time intervals of 0, 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, and 30 minutes, 1, 2, 4, 8, 16, 24, etc. hours measured from the time of each incremental load application.

After consolidation is complete, the weight hanger or lever arm will be removed and the sample and cell shall again be weighed. The apparatus shall then be disassembled and the thawed sample placed in the oven to determine the final water content.

As part of this thaw consolidation test, the index property tests listed below shall be performed on the sample after the final moisture content has been determined (moisture content determined using the entire test specimen). If a specific test requires an air dried (rather than oven dried) sample, the test shall be performed on trimmings obtained when preparing the sample, or if insufficient trimmings are available, upon the oven dried thaw consolidation sample, with this minor deviation from standard procedure noted.

- Particle size analysis (Hydrometer and/or sieve as applicable)
- Atterberg Limits (if minus No. 200 fraction $\geq$ 6%)
- Specific gravity (as specified and required for the hydrometer analysis)
- Organic content (if minus No. 200 fraction $\geq$ 12%)
- USC (Modified)

(v) Calculations

The test data shall be input into the computer for calculations. The following procedures shall be used for determining the percent thaw strain, percent consolidation, percent total settlement and percent excess ice.

1. Percent Thaw Strain

$$\% \text{ Thaw Strain} = \frac{\Delta H_1}{H_I} \times 100$$

ΔH_1: change in height from Load 1, the seating load has already been subtracted from this value (difference between 0.10 minute reading and final reading after Load 1)

H_I: initial height, as measured before the test

Corrected thaw strains will be calculated to account for any differences in the diameters of the cell and sample. Significant gaps occur most often with unlathable materials such as gravel and rock. Volume corrections account for the portion of the settlement value attributable to lateral spreading.

2. Corrected Percent Thaw Strain

2a. Corrected Sample Height

$$H_{corr} = \frac{\text{Initial Sample Volume}}{\pi r^2}$$

H_{corr}: corrected initial sample height

r: radius of cell if sample spread to fit cell or radius of sample taken from post-test diameter measurement

NOTE: Corrected sample height should always be larger than the height of the sample after Load 1; if not, then the sample did not even settle enough to completely conform to the cell or final diameter, therefore the thaw strain value is 0.

2b. Corrected Change in Height

$$\Delta H_{corr} = \Delta H_1 - (H_I - H_{corr})$$

ΔH_{corr}: corrected change in height

2c. Corrected Percent Thaw Strain

$$\text{Corr. \% Thaw Strain} = \frac{\Delta H_{corr}}{H_{corr}} \times 100$$

3. Percent Consolidation

$$\text{\% Consolidation} = \frac{\Delta H_2}{H_{corr}} \times 100$$

ΔH_2: change in height from Load 2 (difference between zero time reading and final reading after Load 2)

NOTE: If the corrected height is less than the height of the sample after Load 1, H_I will be used instead of H_{corr}.

4. Total Percent Settlement

Total % Settlement = Corr % Thaw Strain + % Consolidation

NOTE: If corr. % thaw strain is not needed, % thaw strain will be used.

5. Percent Excess Ice

$$\% \text{ Excess Ice} = \frac{\text{Total } H_2O \text{ Loss}}{\text{Dry Weight}} \times 100$$

Total H_2O Loss: Weight of water lost (as measured) after Load 1

Dry Weight: Dry weight of soil after testing.

(vi) Report

The test results shall be reported on a 3 page computer printout. A copy of the printout is included as Fig 3.8.7 of this section. The first page contains sample data and measurements. The second page contains the strain-log time graphs for thaw strain and consolidation. Page three contains the time readings and final calculations. The following items are presented on the test results printout:

PAGE 1

Date tested and by whom
Boring and sample number
Sample depth
Date input in computer (in title block)
Sample description including visible ice description
    [volume percent, typical size, shape, and orientation
    of the visible ice in general accordance with
    CRREL TR 150 (1966)]
Before test sample sketch
Initial sample measurements:
    height
    diameter
    frozen weight
    frozen moisture content

volume
frozen wet density
frozen dry density

Final sample measurements:
height
diameter (if measured diameter not available, cell diameter is used)
dry weight
final moisture content
volume
final wet density
final dry density

Cell measurements:
number
diameter
weight

PAGE 2

Plot of Load 1: Strain vs. log-time
Plot of Load 2: Strain vs. log-time
Total Settlement

PAGE 3

Load 1 elapsed time and readings
Load 2 elapsed time and readings
Load 1 sample data:
pressure
height after load
change in height
corrected initial height
uncorrected thaw strain
corrected thaw strain
moisture content
weight of water lost

excess ice
volume
wet density
dry density

Load 2 sample data:

pressure
height after load
change in height
consolidation
moisture content
weight of water lost
volume
wet density
dry density

Remarks

The results of the index property tests shall be included with the thaw consolidation test results.

3.8.7 Discussion

In natural permafrost the structure imposes severe behavioural limitations. The ice acts as a discontinuity and dominates the physical behaviour. Thaw consolidation test results then cannot be used to accurately predict settlement rates but may be used as a guide in estimating total settlements. The thaw consolidation test should probably then be regarded as an index test. Sufficient comparisons of laboratory data and field results exist that standard test procedures can be developed (Morgenstern, 1982, personal communcation).

Because of its detailed description and essential simplicity, the test procedure used by Shannon and Wilson Inc. for the Northwest Alaskan Pipeline Company should be considered as a reference test. The test apparatus and procedures reported by the University of Alberta, which permit controlled thaw rates and temperature measurements, are probably unnecessarily elaborate for most commercial applications, although they should be considered in thaw research activities.

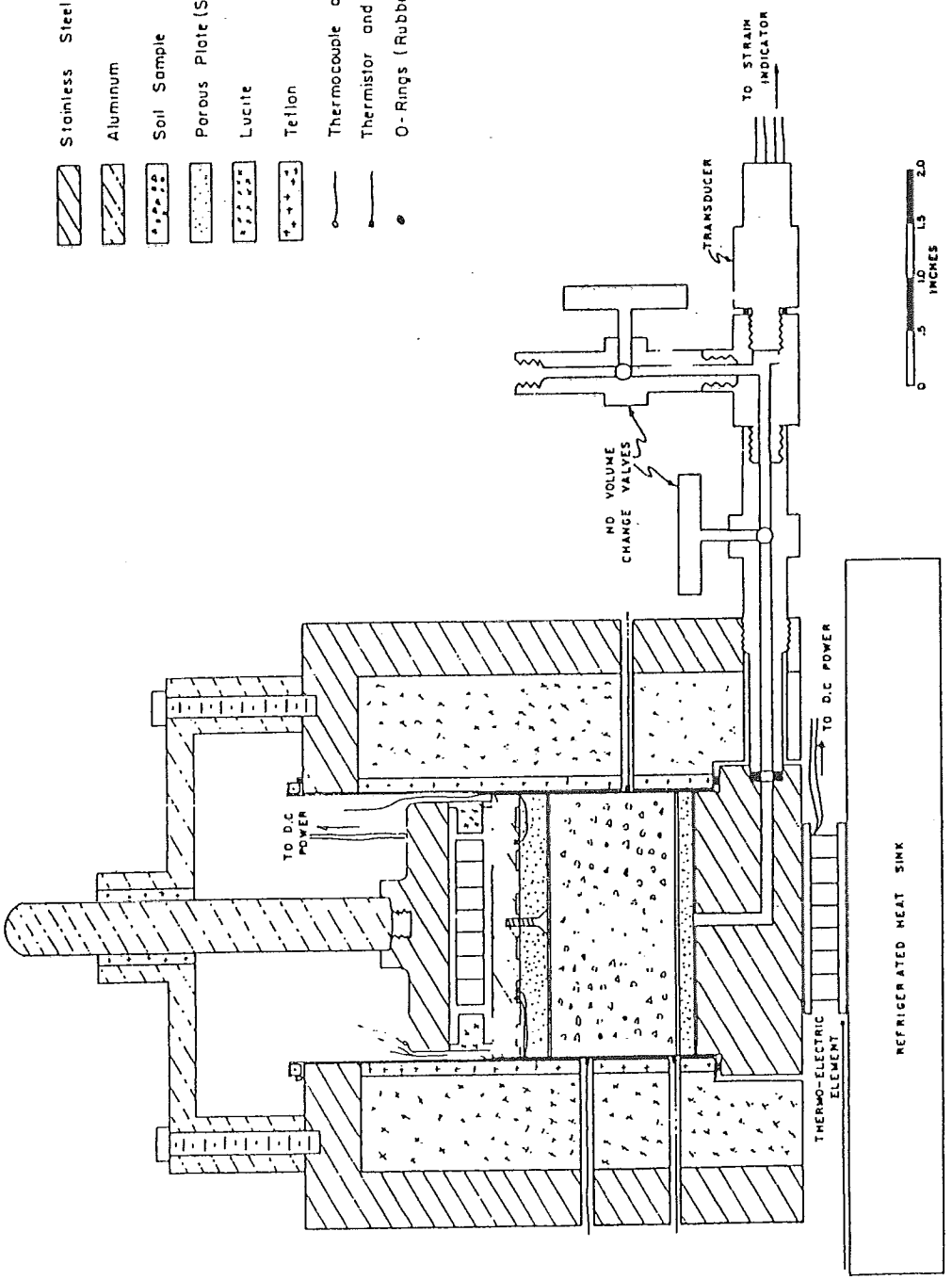


FIGURE 3.8.1 Design of Permode for Thaw Consolidation Testing. (after Morgenstern and Smith, 1973)

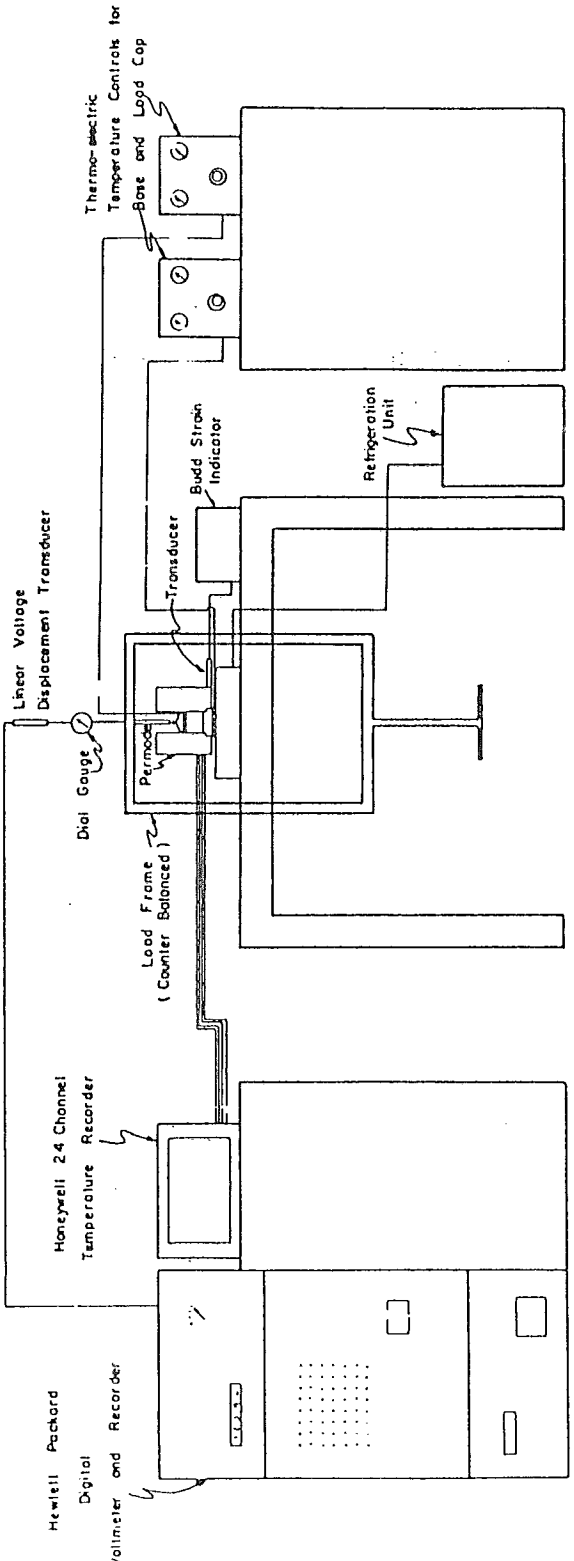


FIGURE 3.8.2 Schematic Diagram for Test Layout for Thaw-Consolidation Test. (after Morgenstern and Smith, 1973)

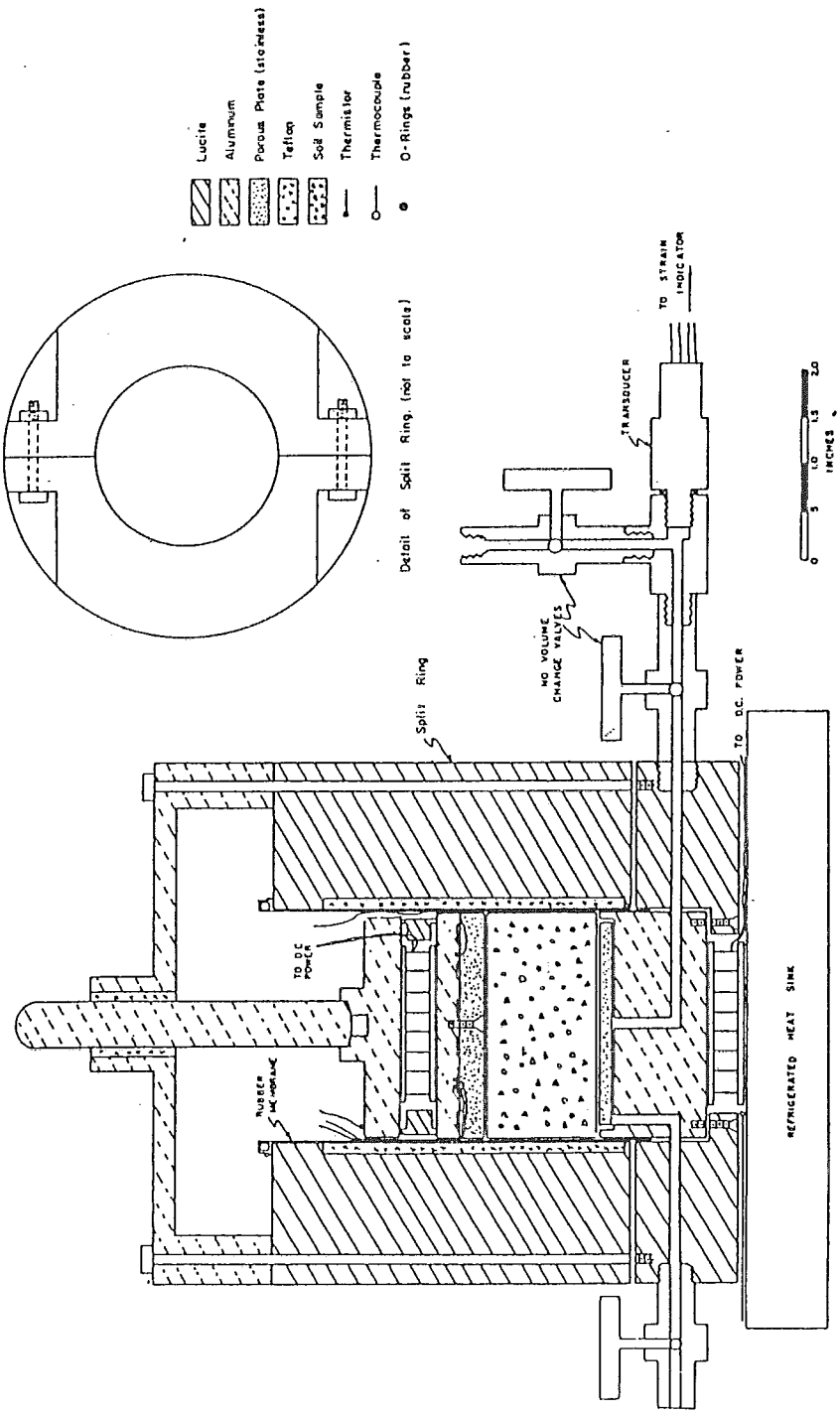


FIGURE 3.8.3 Modified Design of Thaw-Consolidation Apparatus. (after Nixon, 1973)

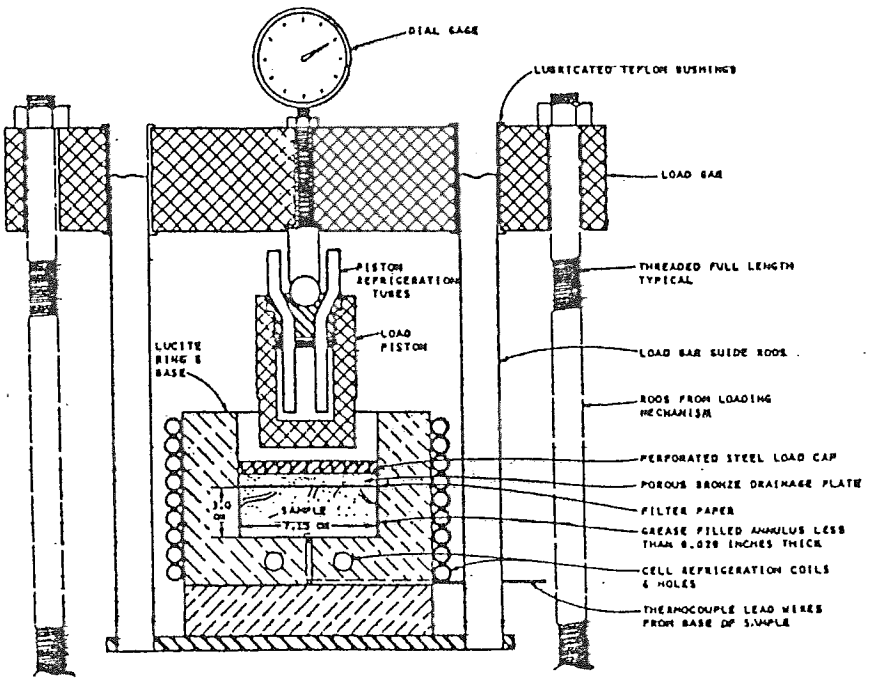


FIGURE 3.8.4 Cross Section of High Pressure Uniaxial Consolidation Cell Assembly. (after Smith, et al, 1973)

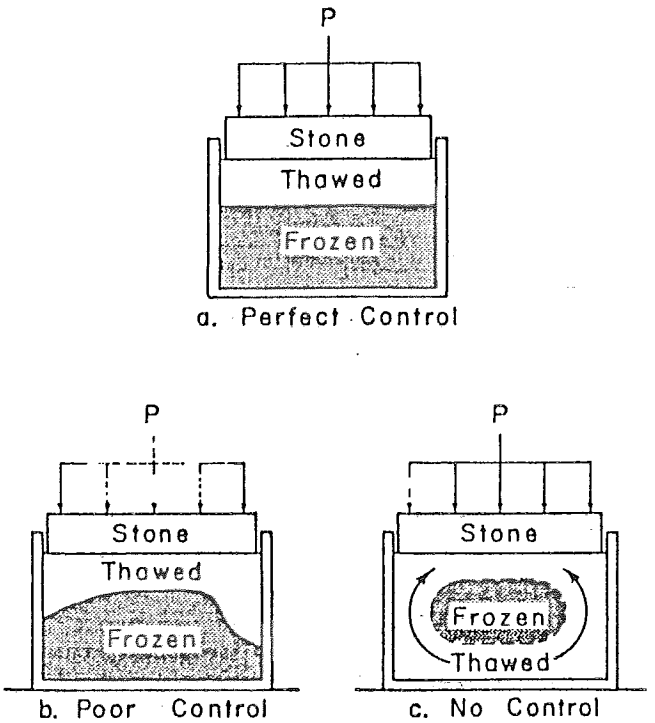


FIGURE 3.8.5 Thawing Frozen Soil Sample in Coldolidormeter with Perfect and Poor Thermal Control of the Thaw Front and with no Control. (after Crory, 1973)

3.9 ELECTRICAL PROPERTIES

Many activities in permafrost terrain require a knowledge of frozen ground electrical properties, such as the dielectric constant (or permittivity) and electrical conductance and resistivity.

The dielectric constant, D, of a soil is a measure of the ability of a dielectric to store electrical energy in the presence of an electrostatic field and, in general, is a basic property reflecting its molecular configuration, composition, texture and porosity. The electrical conductance of a material is the inverse of its resistance to current flow. Both of these latter parameters are sensitive to temperature, porosity, water content and electrical frequency.

Current flow under an electrical gradient in a frozen soil occurs almost entirely through the unfrozen water films. Electrical conduction is related to the thickness of these water films.

Little information is available on the conductance of frozen soils. In general, however, frozen soil cannot be regarded as a good conductor. Ice and mineral particles are relatively poor conductors and the transition layer between them causes frozen soil to have a conductance factor 5 to 20 times less than the same soil in an unfrozen state.

3.9.1 Testing at the University of Toronto (After Olhoeft, 1975)

Olhoeft studied the resistivity, dielectric constant and loss tangent of natural and synthetic permafrost material as functions of frequency, temperature, applied field strength (or current density), water resistivity and content, and uniaxial confining load. The test apparatus and procedures are discussed below.

(i) Apparatus

The measurement techniques used here are all standard methods. The general descriptions of these may be found in many places (ASTM, 1973; von Hippel, 1954; Olhoeft et al, 1973, 1974; Collet and Katsube, 1973; and many others). Both 3-terminal and 4-terminal techniques were applied, with all measurements below 0°C using the 3-terminal technique. Tamamushi and Takahashi (1974) have recently reviewed 4-terminal techniques, finding that the four-terminal method is not always as free of electrode effects as is commonly presumed.

In the 4-terminal technique, an EMR/Hatboro (Weston/Schlumberger) 1410 frequency response analyzer was used from 10^{-3} to 10^{4} Hz. The sample holder design was very similar to that used by Collett (1959), Scott (1965), and others. Electrode materials were platinum, and the cell body was plexiglass.

In the 3-terminal technique, several instruments were used to measure capacitance and conductance or impedance and phase. Samples were approximately 4 to 6 mm thick by 50 mm diameter in a BeO sample holder with molybdenum electrodes (in vacuum) or brass electrodes (in air or below 0°C) as in Fig.3.9.1. In the vacuum chamber, temperature was monitored by type-K chromel-alumel thermocouples using Omega Engineering, Inc. type-J compensators (instead of ice baths) and thermocouple tables. For measurements in air with various quantities of water, temperature was maintained by circulating absolute ethyl alcohol from a Neslab RTE-4 cooler/circulator through copper coils wound around the BEO sample holder. Temperature was measured by a Fenwall UUD-21-J1 bead thermistor accurate to $\pm$0.2°C placed inside the sample.

The actual electrical measurements were made by using whichever of several instruments was appropriate for the frequency and range of impedance required. In Fig.3.9.2 the boxes outline the range of various instruments while the hashed region shows their range of applicability in this investigation (the lower frequency, lower impedance range of the EMR 1410 is its 4-terminal range). Table 3.9.1 outlines the capabilities of each instrument, including ranges and accuracy. Wherever possible, several instruments were used so as to have overlapping measurements as a function of frequency or impedance (or both).

Samples were heated or cooled (thawed or frozen) at a constant rate of 0.5°C/minute with all measurements taken after several hours of equilibration time to allow temperature stabilization. Temperature drift during measurement was less than 0.1°C.

The largest single uncertainty in all of the electrical measurements was due to errors in measurement of the sample thickness,

which is required to calculate or measure C_o, the vacuum capacitance required to reduce the data to dielectric constant and resistivity or conductivity (the loss tangent parameters cancel this error). Thus the minimum error in dielectric constant, resistivity, and conductivity is 2%, the minimum error due to sample geometry uncertainties. To this 2% must be added all errors due to the electrical equipment accuracy and calibration (see Table 3.9.1, usually less than 5%) and errors in frequency or temperature as they would appear in the final parameter.

The errors in the loss tangent are variable, depending upon the range. For loss tangents greater than 10, the error approaches an order of magnitude. For loss tangents less than 0.01, the error is primarily determined by the residual losses of the sample holder which may again be about an order of magnitude. For loss tangents between 0.1 and 2, the maximum error is less than 15% (depending upon the instrument) with minimum errors less than 0.01%.

For the natural permafrost samples where uniaxial confining load was applied and varied, the sample holder was as described above with slight modifications to allow a small press and BLH (Baldwin-Lima-Hamilton Corp.) model C3P1 load cell. A Power Designs Inc. 2005 precision power source powered the BLH load cell and the load was recorded via a HP2401C integrating digital voltmeter. The load was applied to the sample in the direction of the applied electric field. As samples were slices of core (thin discs), a nylon ring was placed around the sample to fill the gap between the edge of the sample and the BeO sample holder. Electrodes were machined from brass of the diameter of the sample, and load was applied so that the sample was between two brass plates and confined by the nylon BeO cylinder (which was wrapped by the copper cooling coils).

(ii) Experimental Procedures

The experimental procedures used are all previously tested methods (ASTM, 1973a,b,c; Olhoeft et al, 1974a,b). Both three and four terminal electrode assemblies were employed with either brass, platinum, or molybdenum electrode materials. Sample holders and insulators were BeO, Al_2O_3, nylon, and teflon. Both bridge and impedance meter techniques gave excellent and consistent results, with several instruments required to cover the complete impedance range and frequency spectrum. General experimental errors were variable as the largest errors in measurement of electrical properties were due to sample geometries. Worst case combined errors did not exceed ±10% in dielectric constant, and in general were much better; worst case errors in loss tangent and resistivity were order of magnitude

due to ranges where sample losses were lower than sample holder and measurement system losses. Typical errors were: ±0.2°C in temperatures below 25°C, ±2°C above 25°C, ±5% or less in dielectric constants; ±5% or less in loss tangents between values of 0.01 and 10, ±10% in resistivity below 10^{11} ohm-m, less than 1% error in frequency.

With three terminal electrode assemblies, either a capacitance bridge or an impedance meter was employed (depending upon impedance range). The bridges measured parallel capacitance and conductance with dielectric constant given by

$$K' = \frac{C_p}{C_0}$$

where C_0 is the vacuum capacitance of the sample holder assembly for that sample geometry, and C_p is the measured sample parallel capacitance. The loss tangent is given by

$$\text{TAN } \delta_E = \frac{G_p}{2\pi f C_p}$$

where C_p is as above, G_p is the parallel conductance of the sample, and f is the frequency of measurement. The vacuum capacitance, C_0, was obtained by the formula given in ASTM (1973a) and verified by direct measurement.

Using an impedance meter, the impedance magnitude and phase angle are measured. The following formulas convert these quantities to the equivalent parallel capacitance and conductance which may then be used with the above equations:

$$C_p = \frac{\text{SIN } \Theta}{wz}$$

$$G_p = \frac{\text{COS } \Theta}{z}$$

where Z is the magnitude of the impedance and Θ is the phase angle (equal to 0° for pure conductance, and equal to -90° for pure capacitance). The loss tangent may also be otained directly from the phase angle by

$$\text{TAN } \delta_E = \text{TAN } (\Theta + \frac{\pi}{2})$$

3.9.2 Testing at CRREL

A. After Hoekstra and Delaney, 1974

The authors studied the complex dielectric constant of four soils, including a sand, a silt and two clays, over a frequency range from 0.1 x 10^9 Hz to 26 x 10^9 Hz. Their apparatus and general test procedures are given below.

> The complex dielectric constant of soils was measured over the frequency range from 10^8 to 2.6 x 10^{10} Hz as a function of water content and temperature. Figure 3.9.3 shows the different methods used to obtain the complex dielectric constant.
>
> The slotted line determinations were all made in wave guide transmission lines and the samples were placed against a short circuit. The dimensions of the sample changed with the size of the wave guide. For example, in the G band (3.95 x 10^9 to 5.8 x 10^9 Hz) the dimensions of the rectangular wave guide were 4.755 by 2.215 cm, and the sample was made 1.67 cm thick; in the K band (18 x 10^9 to 26.5 x 10^9 Hz) the wave guide dimensions were 1.067 by 0.432 cm, and the sample was made 0.3 cm thick. The methods described by Westphall (1954) and Redheffer (1947) were used to measure the dielectric properties of the samples. Calculation of the complex dielectric constant requires measuring the change in the position of the minimum and the VSWR of a standing wave pattern resulting from placing a sample of certain thickness against a short in the wave guide. Determinations were made at one or two frequencies in each band. The method is not suitable for samples with dielectric constants in excess of 20, and for this reason the measurements were limited to water contents of 15% by weight.
>
> In the time domain reflection technique (TDR), soil samples were packed in a coaxial line 20 cm long with an ID of 7 mm. The placing of the sample in the line requires great care, since variations in density will cause unwanted reflections.
>
> The equipment is shown in Fig.3.9.4. A voltage ramp is propagated via a coaxial cable to the tunnel diode. This ramp then opens the tunnel diode, from which a very fast step voltage (rise time about 35 x 10^{-12} s) arises. Such a pulse remains unaltered as long as the propagation characteristics of the line stay the same, but any discontinuity in the line, such as a transition to a section with a different characteristic impedance,

will give rise to a partial reflection and partial transmission of the pulse. The nature of the discontinuity will be indicated by the resulting pulse shapes, whereas its location will be shown by the time relationship between incident and reflected pulses.

For a coaxial line filled with a dielectric the characteristic impedance Z is given by

$$Z = Z_0/K^*(w) \qquad (1)$$

where Z_0 is the characteristic impedance of an air-filled line.

The voltage reflection coefficient p for a discontinuity in the line from impedance Z_0 to Z is given by

$$p = (Z - Z_0/(Z + Z_0) \qquad (2)$$

Combining (1) and (2) and solving for $K^*(w)$ yields

$$K^*(w) = (1 + p)^2/(1 - p)^2$$

The complex dielectric constant can thus be determined from the measurement of the reflection coefficient at a dielectric interface. For a dielectric sample, Z and p will be complex frequency-dependent quantities, and their frequency dependence will be shown in differences between the time domain pulse shapes of the incident and reflected signals.

The use of TDR requires that the reflected pulse be known for all values of t, and this requirement places a major restriction on its use because the decay of any relaxation process must be monitored to completion. The measurement is made at the interface of air and dielectric, and the recording of the reflected pulse must be discontinued when the reflection from the end of the sample reaches the interface. Therefore the maximum time available for measurement is equal to the duration of the return trip of the wave in the sample-filled line. The minimum relaxation frequency measurable for a 20 cm long sample with a dielectric constant of 9 is therefore about 10^8 Hz; this minimum assumes that equilibrium is reached after a time interval equal to 3 times the relaxation time. The results show that the dielectric relaxation of water in soils was higher than 10^8 Hz.

In theory, TDR methods can be extended to frequencies well beyond 2×10^9 Hz, because a step pulse with a rise time of 35×10^{-12} s contains sufficient energy in frequency components higher than 2×10^9 Hz. In practice, however, the occurrence of higher-order modes in coaxial lines sets an upper limit.

Higher-order modes set in if the wavelength in the sample λ_s is less than $\lambda_s \leqq \pi(b + a)$, where a and b are the inner and outer diameters of the coaxial line. To avoid errors caused by this effect, the TDR data were not extended beyond 2×10^9 Hz.

TDR measurements were thus made in the frequency range from 10^8 to 2×10^9 Hz. The complex dielectric constant can be computed for any frequency in this range. In practice the calculation was performed only at a selected number of frequencies, spaced so as to yield a well-defined description of the frequency dependence of K*(w).

By far the largest source of error in TDR dielectric measurement is in locating a time reference for the pulse. The methods developed by Loeb et al (1971) were used in this work. This method was tested on standard samples of alcohols and found to yield data of ±5% in the absolute magnitude of the complex relative dielectric contant and better than ±3% in the frequency of maximum dielectric loss.

A very high direct current conductivity may interfere with TDR measurements since the reflection coefficient of conductivity approaches that of a short circuit. Since the soils used have conductivities of the order of 10^{-2} - 10^{-3} ohm/m, conductivity will begin to contribute to the dielectric loss factor at frequencies below 5×10^8 Hz. The influence of conductivity can be observed from the reflected pulse shape.

In both the wave guide and coaxial line sample holders coolant from a constant temperature bath was circulated through a jacket around the sample holder for temperature control.

B. After Delaney and Arcone, 1982

(i) Apparatus

In dielectric measurements the quantity sought is the complex relative dielectric permittivity K*(f), which is the ratio of the complex dielectric permittivity of the material to that of free space and is expressed as

$$K^*(f) = K' - jK''$$

where $j = \sqrt{-1}$. The quantity K' is the real part and is known as the dielectric constant when K' is much greater than K". The imaginary part K" is known as the dielectric loss factor under the same condition.

In TDR, K*(f) is calculated from Fourier transformation of the time-dependent quantities of incident and reflected pulses propagating along a standard coaxial transmission line. At any particular frequency the ratio of these field strength transformations is the reflection coefficient $\rho(f)$, which is determined by the change in transmission line impedance caused by the insertion of a test sample into the transmission line. In an air-filled line containing a sample at the end, K*(f) is related to $\rho(f)$ through the relation

$$K^*(f) = \left[\frac{1 - \rho(f)}{1 + \rho(f)}\right]^2$$

Obviously, then, $\rho(f)$ is a complex quantity, and great care must be taken to ensure that the relative time delay between incident and reflected waves is correctly determined to avoid errors in computing the reflection coefficient.

A tunnel diode (Fig.3.9.5) generates step waveforms with a very fast rise time in a coaxial waveguide. A sampling oscilloscope records the reflections from the sample interface and from a short circuit at the end of an air-filled line (Fig.3.9.6). The latter reflection gives the incident waveform. The sampled reconstructions of the incident and reflected waves are Fourier-analyzed, using a modification of the Shannon sampling theorem to give the incident and reflected amplitudes at discrete frequencies. The processed data are then converted to relative complex dielectric permittivities.

A Hewlett Packard Model 1815A sampler and an 1108A tunnel diode mount, which produced a rise time of less than 35 ps were used. Therefore, sufficient energy was contained in the pulse spectrum up to 4 GHz, above which the accuracy of the dielectric calculations became seriously impaired because of the difficulty in analyzing the waveforms. One set of incident and reflected waveforms took less than one hour to record and analyze; single frequency measurements using slotted line techniques over the same frequency band take days. The main disadvantage of TDR is that only liquids or fine-grain soils can be placed in the coaxial sample holder. Solid samples could be accurately machined to the annulus dimensions, but we have yet to try this.

(ii) Procedure

The volumetric moisture content of the field samples was measured to determine the range of moisture most appropriate for the laboratory measurements. The soils were oven-dried and then moistened with distilled water to typical soil moisture levels

encountered in the field (0.17 - 0.55 g H_2O/cm^3). After thorough mixing, the sample was carefully compacted into the sample cell (transmission line annulus) to avoid variations in density, which would have caused unwanted reflections. The cell length was 20 cm, which was sufficient to keep reflections from the back of the sample from interfering with those from the front. The soil moisture was determined more accurately at the end of each test by oven-drying the entire sample and measuring the weight of the water loss.

Dielectric measurements were made immediately after packing at room temperature (+25°C). The sample was then quickly frozen to about -25°C by immersing it in a refrigerated bath. This procedure prevented any heterogeneity from occuring from moisture migration during the slow freezing. The connecting transmission line was insulated to minimize thermal conduction along the waveguide from outside the bath. The sample temperature was determined with a copper/constantan short-time-constant thermocouple attached to the immersed sample. The thermocouple could not be placed within the sample since it would have caused unwanted reflections. The temperature was regulated by cycling a quartz heater in a constant refrigeration bath, resulting in ±0.1°C Control. The sample temperature was allowed to stabilize for about an hour after any change in bath temperature.

The dielectric measurement techniques were checked frequently by performing measurements on well-documented substances.

The accuracy of the TDR technique above 3-4 GHz is questionable due to inaccuracies in determining the exact position in time of the pulse traces. The properties of the materials tested below about 0.05 GHz are affected by DC conductivity, but we only observed pulse decay for about 800 ps, during which the tails of the pulses became constant. A secondary relaxation due to conductivity effects would have occurred at about 10,000 ps. However, any rise in K" below about 0.05 GHz due to DC conductivity is not observed in the data, as the pulse level was assumed to remain constant forever. Therefore, the data only show the dipolar contributions to K".

3.9.3 Testing at the Geological Survey of Canada (after Katsube et al, 1976)

Katsube et al conducted laboratory studies on the electrical properties (dielectric constant and resistivity) of natural permafrost samples.

Their apparatus and experimental procedures are discussed below.

The permafrost specimens were cut from core samples drilled at "Involuted Hill" near Tuktoyaktuk. Most of the samples are clay permafrost samples, with some containing organic material. The diameters of the cores ranged from 4 to 5 cm. Disk specimens with thicknesses ranging from 1.0 to 2.5 cm were cut from these cores. The ice content (ϕ) of these specimens varied from 12 to 100 per cent.

The ice content is measured by melting the permafrost samples at room temperature, and then drying them in the oven for over 10 hours at 150°C. The ice content ϕ is determined by

$$\phi = \frac{g_W - g_D}{g_W} \times 100$$

and is expressed in percent, where g_W and g_D are the weights of the specimens in wet and dry conditions.

The specimens are placed in a sample holder that holds six specimens at a time (Fig. 3.9.7). The stray capacitance and leakage resistance between each set of electrodes is in the order of 12 picofarads and 2×10^7 ohms, respectively. Corrections are made for these effects. Each set of electrodes is connected one at a time to the measuring system.

A jacket containing methanol surrounds the sample holder. The jacket is connected to a cooling bath that controls the temperature and the circulation of the liquid through the system. The lowest temperature reached in the sample holder is -16°C. Thin glass thermistors are placed in a position where their tips touch the specimens. The temperature of the specimens is monitored by a digital resistivity meter.

The specimens are measured over the frequency range from 1.0 to 10^6 Hz by the Automatic Electrical Rock Property Measuring system that is described by Gauvreau and Katsube (1975). Since graphite has a larger surface capacitance than iron or stainless steel (10 - 100$\mu F/cm^2$) when in contact with water, graphite discs are inserted between the electrodes and specimen. The contact surfaces of the specimens are slightly heated and melted by the palms of one's hands before making contact with the graphite discs. Good electrode contacts are insured by this method.

Four-electrode systems were considered for elimination of electrode effects, but due to the high resistance that can be expec-

ted at the contacts of the potential electrodes, only the two electrode system is used. However, the electrode effects are not expected to be significant unless the resistivity of the samples is very low.

3.9.4 Testing at the University of Saskatchewan

A. After King et al, 1982

(i) Apparatus and Procedure

The permafrost samples were received in their naturally-frozen state in the form of short lengths of core sealed tightly in plastic film. Test sample storage and specimen preparation at subzero temperatures followed the procedures described by King (1977), except that six cylindrical specimens 50 mm in diameter and approximately 75 mm in length were first prepared for the ultrasonic velocity test. Upon completion of these tests, during which the specimens were not permitted to rise in temperature above -1°C, the specimens were cooled to -9°C and removed from the triaxial cell. They were then machined down to a diameter of 38 mm and two new specimens approximately 38 and 10 mm in length were prepared form each of the six original ones. The specimens of 38-mm length were used for the electrical properties measurements and those of 10-mm length for the thermal conductivity tests. The remaining discs and cuttings were used to measure the bulk density, porosity, water content, and grain-size distribution for the samples.

Upon completion of the electrical properties and thermal conductivity measurements, the specimens were removed from the apparatus, sealed tightly in plastic film, and stored in a freezer cabinet at -9°C. Some months later the specimens were removed and their pore-water salinities measured.

Block diagrams of the apparatus for performing the tests are illustrated. Ultrasonic velocity measurements were made on specimens in the triaxial cell (Fig.3.9.8) and the electrical properties in the pressure cell (Fig.3.9.9). The velocity and electrical properties cells have been described by Pandit and King (1970). Thermal conductivity measurements were made in the divided bar apparatus (Fig.3.9.10).

The ultrasonic velocities and electrical properties were measured following essentially the procedures described by Pandit and King (1979), except that the ultrasonic velocities were measured only under a hydrostatic stress of 0.34 MPa at constant temperatures

in the range -10 to -1°C. In no case was the temperature permitted to rise above -9°C, because it was necessary to preserve the specimens in their original frozen state for subsequent tests. The electrical properties measurements were made on specimens subjected to a hydrostatic stress of 0.34 MPa at constant temperatures in the range -13 to -1°C. Thermal conductivity measurements were made following essentially the procedure described by King (1979), with the specimens subjected to a uniaxial stress of 0.70 MPa at mean temperatures in the range -10 to -1.3°C.

Pore-water salinities were measured by placing a frozen specimen of known bulk and pore volume in a known volume of distilled water. Upon thawing, each of the specimens disintegrated and the pore water mixed with the distilled water. The resulting solution was decanted and the salinity determined by measuring its electrical resistivity.

A study of experimental errors indicates that the measured compressional-wave velocities are expected to be within ± 1 per cent and shear-wave velocities within ± 2 percent; the measured electrical resistivities and phase angles to be within ± 10 per cent; and the measured thermal conductivities to be within ± 5 percent of the true values.

B. After Pandit and King, 1978

Refer to section 3.11.4 of this report.

TABLE 3.9.1 EQUIPMENT AND SPECIFICATIONS FOR ELECTRICAL PROPERTIES MEASUREMENT
(after Olhoeft, 1975)

MANUFACTURER	MODEL	FREQUENCY (Hz)	IMPEDANCE RANGE (Ohms)	ACCURACY (%)	LOSS TANGENT	VOLTAGE (V)
General Radio	1621*	10 to 10^5	10 to 10^{16}	0.005	10^{-7} to 10	0.1 to 150
General Radio	1620-AP*	50 to 10^5	10^4 to 10^{12}	0.5	10^{-4} to 10	1 to 30
General Radio	1682	10^6	50 to 10^7	1.0	0.004 to 10	-
Hewlett-Packard	4800#	5 to $5x10^5$	1 to 10^7	5	0.1 to 9.5	0.0015
Hewlett-Packard	4392A#	DC	10^6 to 10^{13}	5	NA	1 to 1000
Hewlett-Packard	410C#	DC	1 to 10^7	5	NA	0.5
EMR-Hatboro	1410#	10^{-3} to 10^4	10^3 to 10^6	5	0.003 to 286.	0.015 to 15
Wayne-Kerr	B201/SR268*	10^5 to 10^7	10^3 to 10^8	0.1	0.004 to 10	7.5
Data Precision	2540A1#	DC	1 to 10^7	0.1	NA	0.5
Guildline	9820#	DC	10^6 to 10^{16}	0.1	NA	1 to 1000

Accuracy is rated for impedance measurement; loss tangent accuracy is variable depending upon the exact impedance seen by the instrument, the loss tangent magnitude, and the frequency of measurement (see individual instruction manuals). Resolution is generally 3 to 6 digits.

NA - not applicable. * - bridge. # - impedance meter or ohmmeter

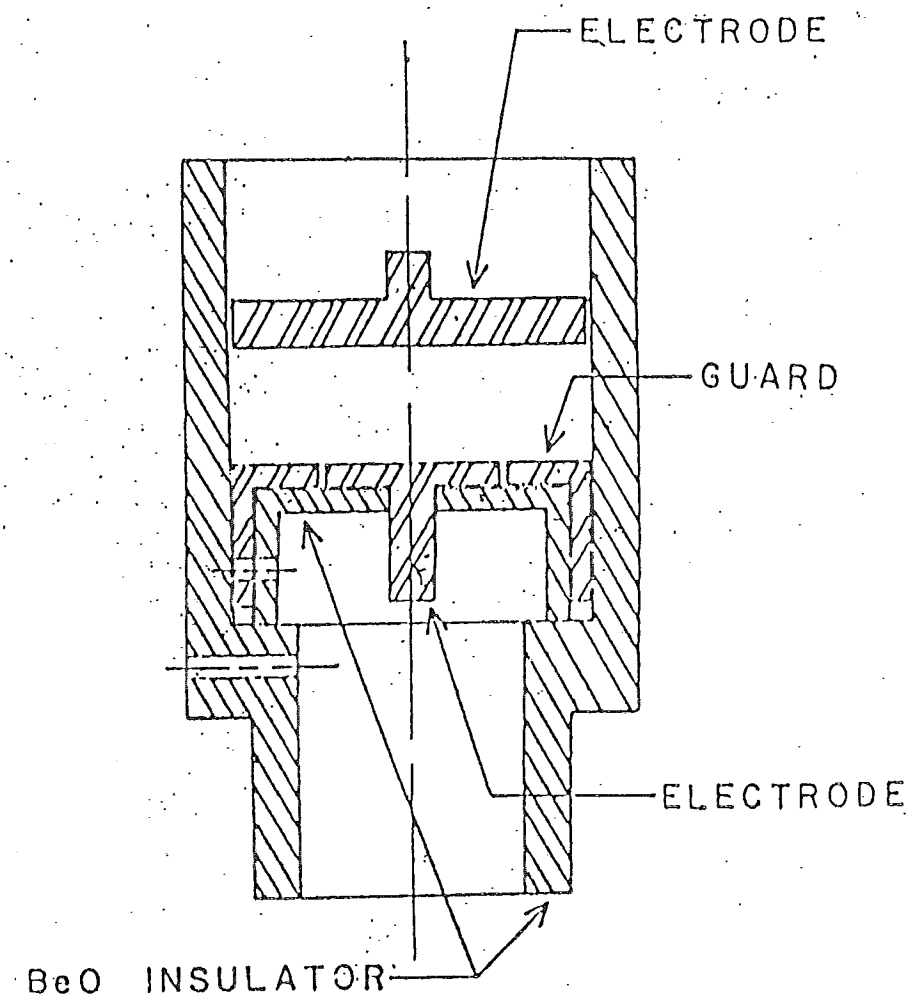


FIGURE 3.9.1 Three-Terminal Sample Holder
(after Olhoeft, 1975)

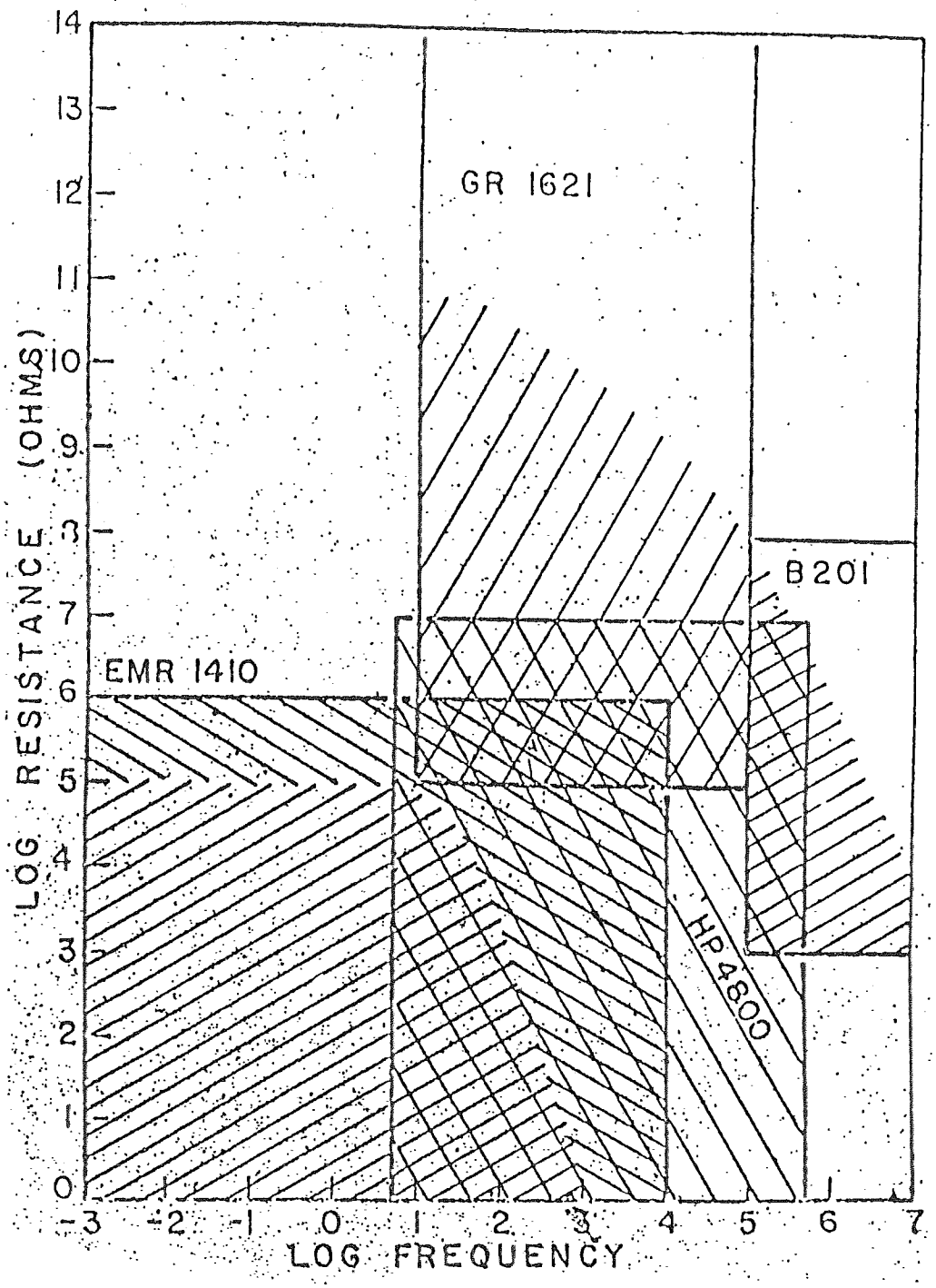


FIGURE 3.9.2. Ranges of Resistance Measurement Capability at Various Frequencies for the Instruments used in Olhoeft (1975) thesis.

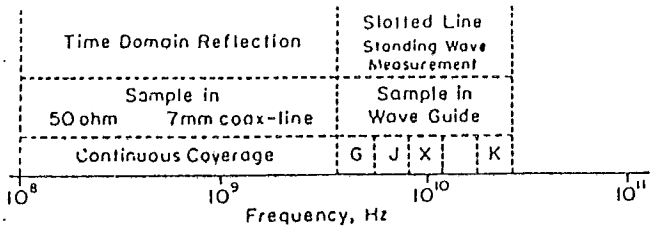


FIGURE 3.9.3 Schematic representation of the methods used to measure the complex dielectric constant of soils. The capital letters indicate the common denominations of the wave guide bands.
(after Hoekstra and Delaney, 1974)

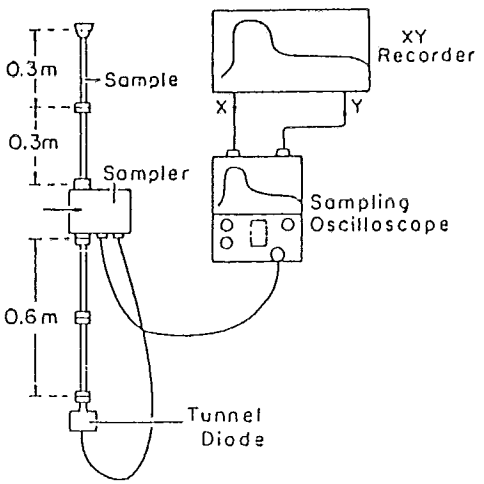


FIGURE 3.9.4 Schematic Diagram of Experimental Apparatus used in Time Domain Measurements
(after Hoekstra and Delaney, 1974)

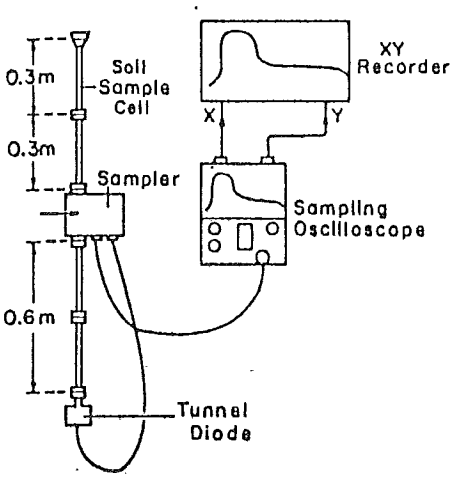


FIGURE 3.9.5 Schematic Diagram of TDR Equipment Using Coaxial Waveguide (after Delaney and Arcone, 1982)

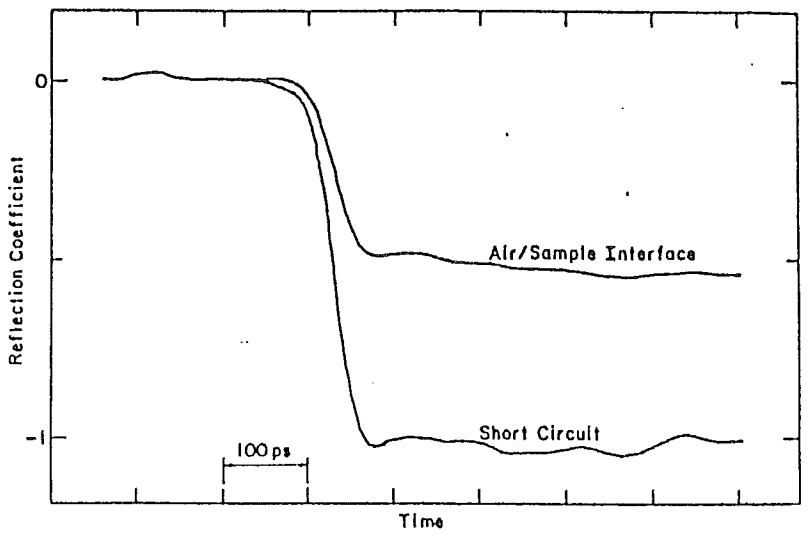


FIGURE 3.9.6 Typical TDR Signals Reflected From an Air/Sample Interface and From a Short Circuit (after Delaney and Arcone, 1982)

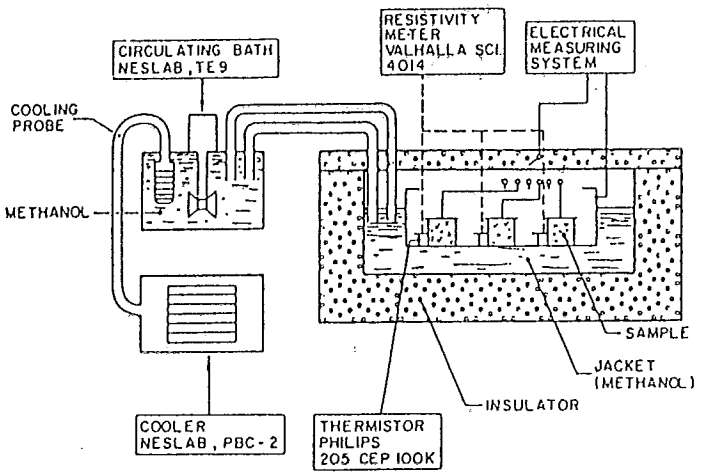


FIGURE 3.9.7 Block Diagram of the Electrical Measuring and Cooling System
(after Katsube et al, 1976)

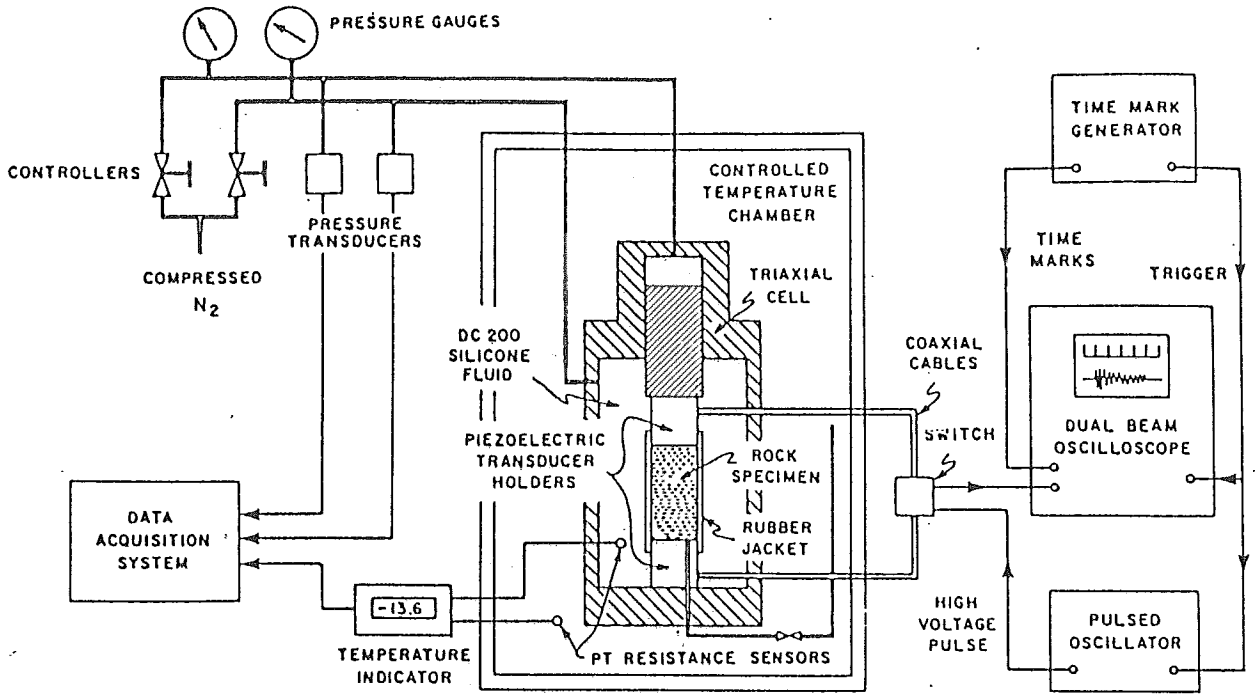


FIGURE 3.9.8 Block Diagram of Apparatus for Ultrasonic Velocity Measurements (after King et al, 1982)

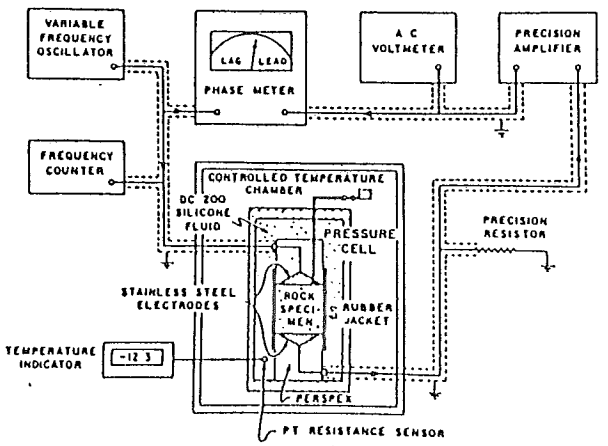


FIGURE 3.9.9 Block Diagram of Apparatus for Electrical Property Measurements (after King et al, 1982)

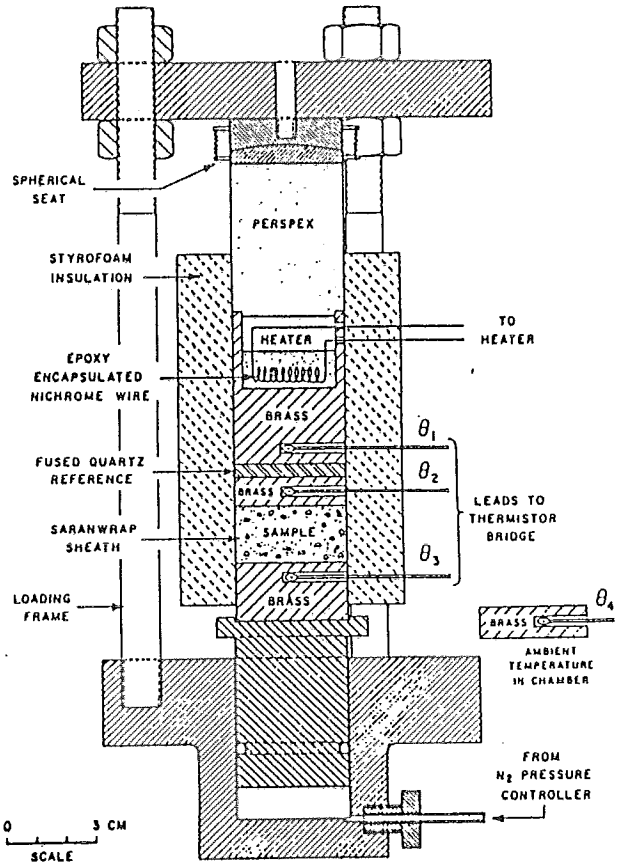


FIGURE 3.9.10 Cross-Section of Divided-Bare Thermal Conductivity Apparatus (after King et al, 1982)

3.10 SOIL CHEMISTRY, MINERALOGY AND PORE WATER CHEMISTRY

3.10.1 Introduction

There are few accounts in the literature which specifically deal with the mineralogy and soil and pore water chemistry of frozen soils. Many of the common test methods require that the sample be in an unfrozen state. This section outlines some of these methods.

3.10.2 Soil Chemistry

The chemical composition and behaviour of a soil will affect its engineering performance. The common index tests (Section 3.2) do not always provide enough information with respect to the effects of chemical behaviour. Clays are particularly sensitive to the chemical composition of the interstitial and pore waters.

There is a notable lack of literature that deals specifically with the measurement of chemical properties of frozen soils. In one of the few published reports, Lapina (1973) studied the effect of freezing on chemical processes in clays by studying the pore water chemistry. Other authors have used this method to study chemical properties of unfrozen soils. These procedures are discussed in Section 3.10.4.

The remainder of this section will deal with some common chemical tests performed on unfrozen soils, and their possible applicability to the study of permafrost.

A review of chemical processes in soils known as "geochemistry" is given by Krauskopf (1979). Although laboratory procedures are not described in this book, much of the theoretical basis of geochemistry is explained.

One of the most important chemical processes that occurs in soils is the dispersion of clays. Dispersive clays are fine-grained soils which are highly erodible by a process in which colloidal clay particles go into suspension in water which is still or moving at a velocity much less than that required to erode ordinary clays. These soils tend to have a large sodium ion concentration, while other clays have large amounts of calcium and magnesium.

Tests used to identify dispersive soils are generally performed on unfrozen soil samples. The results of such tests would be useful since some soils may become dispersive when thawed or experience an increase in unfrozen water content.

The preferred procedure for identifying dispersive clays is to perform a series of tests on a large number of samples; namely the pinhole tests, SCS dispersion tests, pore water salt concentration, and the crumb test (Sherard et al 1976b). The pinhole test is the most reliable test since it simulates the erosive action of a concentrated leak by passing distilled water through a 1.0 mm diameter hole (made by a pin) in an undisturbed soil specimen. In dispersive clays, the effluent water will be coloured by the eroded clay particles, whereas the water will remain clear if no erosion occurs. The procedure for the pinhole test is described in detail by Sherard et al (1976a).

The concentrations of various water-soluble chlorides in a soil sample may be determined by ASTM Standard Test Method D1411.

The following procedure for the measurement of soil salinity through its electrical conductivity has been suggested by Martin (1970):

> Scope
>
> The method is a rapid, simple procedure for the determination of soluble salt in soils. The electrical conductivity of the

supernatant liquid is used to approximate the soluble salts present in the soil pore fluid. The method is not intended to be precise; however, on a relative basis reliable comparisons can be made. At any one location, the method permits very small changes in pore fluid salt concentration to be accurately measured.

Special Apparatus

(i) **Alternating-Current Wheatstone Bridge**, suitable for conductivity measurements.

(ii) **Conductivity Cell**, with a cell constant between 0.4 and 1.0. Design of the cell should be such that air bubbles are not trapped in the cell during filling and should require a small volume of solution, about 5 ml.

(iii) **Centrifuge** This is optional.

Reagents

(i) **Purity of Reagents** Reagent grade chemicals or equivalent, as specified in ASTM Methods E 200, for Preparation, Standardization, and Storage of Standard Solutions for Chemical Analysis, shall be used in all tests.

(ii) **Purity of Water** Distilled water or water conforming to ASTM Specification D 1193, Reagent Water.

(iii) **Potassium Chloride, Standard Solution (0.020 N)** Dissolve 1.49 1 g of potassium chloride (KCl) in distilled water and add water to make 1.000 liter at 25C.

Procedure

(i) The electrical conductivity measurement for soluble salt determination should be made on soil that has not been dried. The water content must be determined in order to ascertain how much wet soil should be used for the soluble salt determination. Determine water content in accordance with ASTM Method D 2216, Laboratory Determination of Moisture Content of Soil.

Water content, percent, W = g H_2O/100g of soil

Add wet soil into a 50 ml beaker to give the equivalent of 15.0 ±0.1 g of dry soil. Calculate the wet weight, W_r, to add as follows:

$$W_r = 15 \left(1 + \frac{W}{100}\right)$$

(ii) Add distilled water to make the total water content 30.0 ±0.2 ml. The volume of water required in milliliters equals $(45 - W_n)$. This gives a 2:1 water:soil slurry.

(iii) Stir well and allow 20 to 30 min for equilibration with intermittent stirring during this period.

(iv) Measure resistances with an a-c Wheatstone bridge in accordance with the manufacturer's instructions. Read the resistance of the 0.02 N KCl solution (R_0). Read the resistance of the clear supernatant liquid from the water:soil slurry (R).

NOTE: For fat clays low in salt content, it may be difficult to obtain enough clear supernatant liquid for conductivity measurement. The soil and water can be weighed into a centrifuge tube, tightly capped or sealed to prevent evaporation, and centrifuged to obtain a clear supernatant liquid. Plastic wrap held on with rubber bands provides a very good moisture seal.

Calculation

(i) Express the results as grams of readily soluble salt per liter, RSS, with seawater salt as the reference salt. When the dissolved salts contributing to the electrical conductivity differ markedly from seawater composition, the absolute value of grams of salt per liter may be inaccurate. However, even small relative changes in salt concentration are accurately measured so long as the salt composition at the location under investigation does not change markedly. The plot of R_0/R versus grams of salt per liter gives a unique curve whether sea water or reagent grade sodium chloride was used as the salt.

The ratio R_0 to R obtained from the electrical conductivity measurement on 0.02 N KCl solution and on the 2:1 water:soil slurry respectively are the experimental data. These data give directly the soluble salt concentration, RSS, present in the supernatant of the water:soil slurry used. If the salt concentration in the pore fluid of the soil is to have any significance, it is essential that the salt concentration be corrected for the water content difference between the conductivity test condition and the water content of the soil for which the pore fluid salt concentration is desired. Hence:

$$\text{Pore fluid salt concentration} = \text{RSS} \times \frac{200}{W_n}$$

where W_n = water content of soil (g H_2O/100 g of soil) at which the salt concentration is desired.

Alternatively, conductivity data could be reported as R_o/R for a specific soil water content of 200 percent.

3.10.3 Soil Mineralogy

A general procedure for the mineralogical analysis of a soil sample is outlined in Table 3.10.1. Detailed procedures for most of the tests mentioned in Table 3.10.1 are given by McKeague (1978).

The sieving and (wet) sedimentation methods of grain-size analysis are performed by ASTM standard procedure D422-63, as described in section 3.2.4. The infra-sizer method is a rapid technique which separates the grain sizes by air elutration (Yong and Warkentin,1975).

After or during the grain size analysis, the soil sample is split into coarse (gravel, sand, silt) and fine (clay) fractions, on the basis of the No.200 sieve. Standard chemical and geological methods are used to study the composition of the coarse fraction. Microscopic studies and other methods are used to identify the various mineral groups which are present (quartz, feldspar, micas, etc.).

The clay-size fraction is not easily examined by the above methods, with the exception of microscopic examinations. Many of the test procedures mentioned in Table 3.10.1 do not directly identify clay minerals, however, they give results which may be compared to standard values for the various minerals. General texts on clay mineralogy (Yong and Warkentin,1975; van Olphen,1977; and others) describe the theory behind these tests and give procedures.

X-ray methods are used to identify silt and clay minerals in a soil sample by the measurement of their lattice spacings. X-ray diffraction

patterns of powdered samples of clay minerals are published in the literature. Although the presence of specific minerals may be established by this method, it is difficult to determine their quantities.

Differential thermal analyses may be performed in order to identify clay minerals by their behaviour during heating. Temperature variations in a clay are measured relative to an inert material to produce a "thermogram". (An inert material is defined as a substance which does not exhibit any heat reactions in the temperature range considered. Dry calcined aluminum is commonly used). Constituent minerals in a sample may be identified by comparison to standards (Lambe,1951). Differential thermal analyses may also be performed by cooling a sample. Anderson and Tice (1971) used a variation of the method, differential scanning calorimetry (see section 3.2.2.2) to indirectly measure the unfrozen water content of frozen soils.

The cation exchange capacity (CEC) of a clay material is defined as an excess of ions in the zone adjacent to the charged surface or layer which can be exchanged for other ions (van Olphen,1977). The value of CEC may be used to determine the mineralogical composition of the clay sample, since specific clay minerals exhibit different ranges of values. The CEC of a clay sample may be found by several techniques, including standard chemical, X-ray, and radioactive methods. A number of references to these procedures are given by van Olphen (1977).

The surface area per cent mass of clay particles serves as an indicator of their mineralogy, and can be related to other properties, such as unfrozen water content. Surface area may be determined by the ethylene glycol retention method (Bower and Goertzen 1959).

3.10.4 Pore Water Chemistry

The chemistry of the pore or interstitial waters affects many of the properties of a frozen soil discussed in this report. The presence of salt ions has the most dramatic effect, by lowering the freezing point of the soil. The pore water chemistry is governed by the environmental conditions during clay formation and subsequent leaching, rather than by the mineralogy of the clay (Dascal et al,1977). Reports on the chemical analysis of the pore waters of frozen soils are scarce. The few accounts that exist (such as Iskandar,et al 1978) report that frozen samples were melted, and pore water samples taken as for unfrozen soils.

Iskandar et al (1978) caution that cores of frozen soils be trimmed before pore water is extracted, so that disturbance and chemical contamination caused by wash boring may be avoided. Edmunds and Bath (1976) recommend that compressed air be used in the recovery of samples for pore water chemistry, in order to minimize contamination. If a liquid drilling fluid is used, the inclusion of a lithium chloride tracer is recommended, so that the extent of contamination in permeable cores may be easily recognized.

There are several methods for the extraction of pore water samples from soil (Edmunds and Bath 1976):

1) hydraulic or gas squeezers
2) elutriation and leaching with distilled water
3) multiple washing techniques
4) centrifugation

Each of the above methods extracts only a fraction of the total pore fluids in the sample, and are subject to fractionization i.e. chemical variations within the sample. Some constituents are extracted more quickly or easily than others, so that the extract may not be

representative of the pore fluid. A discussion of this effect is given by Edmunds and Bath (1976).

The chemical constituents of pore water are affected by temperature. This is of particular importance for frozen soils at temperatures near $0^{o}C$. For this reason, it is recommended that the extraction of pore water take place at or near the drilling site, preferably no later than 2 hours after core recovery. Measurements of pH and bicarbonate concentrations should be made immediately so as to obtain values near to the in-situ concentration.

Although it is beneficial to perform chemical analyses as soon as possible after extraction, storage of the pore water extracts may be necessary. Edmunds and Bath (1976) recommend that acidified samples be stored in polystyrene bottles with polypropylene screw caps. Evaporation loss should be minimized when opening the bottles.

A summary of methods, sample sizes, and accuracy of measurement for chemical analyses of pore water is given in Table 3.10.2.

Edmunds and Bath (1976) used the following procedure for centrifuge extraction of pore waters from rock samples. The volume of fluid extracted by the process depends on the weight of sample, pore size distribution of the sample, the degree of initial saturation, the centrifuge dimensions, and rotation speed. The exact procedure used will vary depending on the type of sample and the purpose of the pore water investigation.

1) Place sample inside a polyethylene bag and crush. Transfer pea size fragments immediately to covered centrifuge buckets (to prevent evaporation loss). The maximum sample weight should be about 180 g in each low speed bucket and 40 g for high speed buckets.

2) Balance the buckets to a tolerance of $\pm$ 0.1 g.

3) Spin samples for 1 hour at desired speed. The time required for sufficient pore water extraction will depend on the porosity and permeability of the sample.

4) After spinning, combine fluids from the buckets and filter. Stabilize the water by adding 3x high-purity HNO_3 or HCl per ml water.

Iskandar et al (1978) used this method to extract the interstitial waters from cores of sub-sea permafrost. Filtering centrifuge tubes made of plastic and Teflon were used to minimize contamination.

It is recommended that procedures for determination of the chemical constituents of pore water be performed on saturation extracts where possible, since this gives a closer approximation of the salinity of the natural soil solution than does weaker soil-water solutions (McKeague,1978). These weaker extracts may be useful for certain tests. Iskandar et al (1978), extracted interstitial water by shaking a soil sample with 20 ml of deionized water for 1 hr. This sample was used for electrical conductivity measurements.

A procedure for the vacuum extraction of interstitial waters is given by McKeague (1978):

Soluble Salts in Saturation Extract (conductivity, cations and anions)

1) Weigh 200 to 1000 g (usually 250 g yields an adequate volume of extract) of air-dry soil of known water content into a plastic or metal container with lid.

2) Add distilled water from a large burette and stir the mixture with a spatula until the soil is saturated. Consolidate the mixture by tapping the container periodically on the bench during mixing. At saturation, the soil paste glistens as it reflects light, flows slightly when the container is tipped, and slides freely off a spatula for all soils except those of high clay content.

3) Cover the container and allow the samples to stand for at least an hour; then re-check the criteria for saturation. If

the paste has stiffened markedly or lost its glisten, add water and mix again. If free water has accumulated at the surface, add a weighed amount of dry soil and remix.

4) Record the volume of water added and calculate the saturation percentage as the total weight of water in the sample (that added and hygroscopic water) as a percentage of the oven-dry weight of soil. Alternatively, the saturation percentage may be determined by taking a subsample of the saturated paste, oven-drying it at 105°C and reweighing. If this method is used it is not necessary either to weigh the initial soil sample or to measure the water added.

5) Allow the saturated paste to stand 4 hours or more and transfer it to a Buchner funnel fitted with a low ash, highly retentive filter paper. Apply vacuum and collect the filtrate in a test tube or bottle. If the initial filtrate is turbid, refilter it. Terminate filtration when air begins to pass through the filter. One drop of 0.1% sodium hexametaphosphate solution may be added for each 25 ml of extract (to prevent precipitation of $CaCo_3$).

6) Measure the conductivity of the saturation extract using a Wheatstone bridge or other conductivity bridge and a conductivity cell with cell constant of about 1 cm^{-1}. (See Bower and Wilcox,1965, for details). Report conductivity as millimhos/cm at 25°C. Standardize the cell against 0.01 N KCl (0.7456 g of KCl made to 1 with distilled water at 25°C). At 25°C, the conductivity of this solution is 1.4118 mmhos/cm.

7) Determine cations in solution by standard flame emission or atomic absorption procedures. Alternatively complexometric methods may be used for Ca, Mg, etc. (see Bower and Wilcox, 1965). Reliability of data should be checked by analyzing extracts of standard soil samples and comparing the results obtained with "best" values. The cations that are usually determined are: Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}.

8) Determine anions in solution by standard methods given by Bower and Wilcox, 1965. The anions commonly determined are:

$$CO_3^{2-},\ HCO_3^{-},\ Cl^{1},\ SO_4^{2-}$$

As with cations, reliability of data should be checked by analysis of standard soil samples of known salt content.

TABLE 3.10.1 Procedure for Mineralogical Analyses of Soils (after Yong and Warkentin, 1975)

(A) *Grain-size analysis and fractionation.*

1. Sieving methods.
2. Sedimentation methods (wet analysis).
3. Infra-sizer method (air elutriation).

(B) *Methods for coarse particles.*

1. Chemical analysis.
2. Microscope studies.
   (a) Binocular miscroscope (0.25 mm).
   (b) Polarizing microscope (5.0 microns).
   Refractive indices by immersion.
   Determination of minerals by their optical properties.
   (c) Staining methods.
   (d) Particle shape, size, sphericity, angularity, statistical counts of particles, composition and texture studies.
3. Specific gravity determinations.
4. Heavy-liquid analysis.
5. Electromagnetic separation.

(C) *Methods for clay-size fraction.*

1. X-ray diffraction and fluorescence.
2. Differential thermal analysis.
3. Optical (microscope) study of aggregates.
4. Electron microscopy.
5. Chemical methods.
   (a) Bulk chemical analysis
   (b) Chemical treatment for removal of specific substances.
   (c) Organic content analysis.
   (d) Cation-exchange capacity determination.
   (e) Potash determination.
   (f) Glycol or glycerol retention.
6. Surface area determination.
7. Infrared methods.

TABLE 3.10.2 Summary of Analytical Methods Used for Microanalysis of Interstitial Waters (after Edmunds and Bath, 1976)

Ion	Minimum Solute Weight Required for Volume and Method Stated	Ideal Sample Volume Required for Dilute Waters, ml	Optimum Precision	Method
Na	<15 ng[a]	1 ml diluted to 5 ml	±2-3%	AA spectroscopy using K^+ buffer and air/acetylene flame
Ca	<80 ng[a]		±2-3%	
K	<80 ng[a]		±4%	AA spectroscopy using $NaCl/LaCl_3$ buffer and air/acetylene flame
Mg	<14 ng[a]	2 ml diluted to 5 ml	±2-3%	
Sr	<240 ng[a]		±2-3%	
Li	<35 ng[a]	1 ml	±1%	AA spectroscopy-direct
HCO_3	50 g	1 ml	±3%	Back titration
SO_4	500 g	10 ml	±2%	Titration with barlum perchlorate - thorin indicator
Ci	100 g	1 ml	±2%	AAS
	500 g	5 ml	±2%	Argentometric
NO_3	50 ng	1 ml	±2%	UV spectroscopy
F	50 ng	1-2 ml	±10%	Ion selective electrode using TISAB buffer
Br	250 ng	1 ml	±10%	Neutron activation
Fe	0.2 ng[b]	1 ml[b]		
Ni	0.6 ng[b]	1 ml[b]	±5%	
Cu	0.2 ng[b]	1 ml[b]	to	Flameless AA spectroscopy using standard addition
Pb	0.2 ng[b]	1 ml[b]	±10%	
Zn	1 pg[b]	1 ml[b]		
pH		1 ml	±0.03 pH	Micro pH electrode

[a] Solute weight given corresponds to that required to give sensitivities equivalent to 1% adsorption by AAS.

[b] Values quoted refer to Perkin Elmer (HGA-74) and to the volume required to make 12 replicate 50- 1 injections including rinsing.

3.11 ACOUSTICAL AND GEOPHYSICAL PROPERTIES

Velocities of various subsurface materials are commonly obtained during field seismic surveys. Interpretation of results can be difficult in many cases if the condition of the materials is not known. Laboratory studies on soils or rocks are especially useful in investigating their dynamic properties because the effect of specific parameters including composition, temperature, pressure and water content can be investigated under controlled conditions.

Either resonance or pulse transmission techniques are usually used in the laboratory to determine the dynamic properties of frozen soil or rock. The resonance or sonic method consists of inducting vibrations in the samples and determining resonant frequencies, from which the wave velocities are calculated. The pulse transmission technique is based on measurements of travel-times of sonic and ultrasonic pulses. This latter method is directly comparable with seismic travel-time determinations, apart from the difference in wave-length.

Parameters that influence the compressional and shear wave velocities include grain size and lithology, total moisture content and the nature of interstitial fluid, temperature and degree of freezing of interstitial water, porosity and pore structure, confining pressure and degree of cementation. Since most soils and rocks contain water, they show a different velocity below the freezing point than above it. The change in velocity, however, can occur gradually as temperatures decrease below 0°C if the water is saline or because of the interstitial forces in fine-grained soils.

Velocities are higher in frozen soils or rocks than in the same unfrozen material. The largest increase in compressional wave velocity from the unfrozen to the frozen state occurs in unconsolidated sediments.

Surprisingly little published data is available on laboratory studies in this area. Apparatus and test procedures from a few available recent studies are described below.

3.11.1 Testing at Hardy and Associates, Calgary (After P.B.Fransham et al, 1982)

(i) Introduction

Surface and borehole seismic surveys can provide substantial back-up data on the nature and distribution of ice, if sufficient calibration of the wave velocities is available. It has been documented that the seismic velocities are a function of the temperature, ice content, and mineral composition of the soil. To better understand this phenomenon and to interpret the growth of ice lenses at the Illisarvik drained lake experimental site, field and laboratory investigations of the compressional wave velocities of Illisarvik soils were carried out. Ultrasonic testing techniques were used to measure the compressional wave velocity.

In addition to the field testing, a series of laboratory experiments were carried out on compacted samples of kaolinite and sand. The purpose of these tests was to determine the relationships between the compressional wave velocity, clay content, moisture content, and bulk density. All of the tests were carried out over a temperature range from -9.0 to 0.0°C.

(ii) Apparatus and Procedures - Laboratory Testing

Since the samples with high moisture contents tended to fail at temperatures close to freezing, it became necessary to incorporate a triaxial pressurizing system into the apparatus used for the laboratory testing program (Fig.3.11.1). In the initial stages, all testing was carried out under uniaxial loads.

Basically, the apparatus consists of an insulated chamber inside a cold room. The chamber is temperature controlled and allows for sample testing at varying temperatures. Ultrasonic compressional wave velocities were measured using a commercially available testing machine (PUNDIT). The PUNDIT generates a voltage pulse that is transformed into mechanical energy through piezoelectric crystals. A second transducer picks up the mechanical

pulse and transforms the pulse back to a voltage. Auxiliary equipment allow for wave-form display on an oscilloscope and for the recording of the travel time through the sample on an X-Y recorder. The Y axis of the recorder measures the travel time, while the X axis records temperature. In this manner, it is possible to monitor the complete velocity temperature curve with a minimum amount of supervision by the operator. Upgrading of the equipment has included a second thermistor to measure the temperature at the centre of the sample as well as just below the upper transducer. This allows for much greater control of the temperature within the sample and provides a measure of the temperature variations within the samples. A linear voltage displacement transformer (LVDT) was used to measure the axial deformation as the sample was tested. Since it was no longer possible to monitor all of the functions on an X-Y plotter, a data-acquisition system was used to record all of the data. The data was subsequently transferred to the main computer for plotting.

3.11.2 Testing at the Geological Survey of Canada (After P.J.Kurfurst 1976, 1977)

(i) Introduction

Approximately 50 of the collected samples were chosen to represent a variety of surficial materials ranging from organic peats to sands, silts, clays, and their mixtures.

For the ultrasonic measurement tests it was necessary to prepare 5 cm diameter specimens from larger core samples in their frozen state. A multipurpose grinder, installed in a temperature-controlled room, was used to grind the cylindrical and flat surfaces of the specimens. The temperature during sample preparation was held at approximately -10°C, and DC 200 silicone fluid was used as a coolant in the grinding process. Details of the sample preparation were similar to those described by Kurfurst and King (1972).

(ii) Equipment and Testing Procedure

A block diagram of the apparatus used to measure the ultrasonic wave velocities is shown in Fig.3.11.2. The apparatus consists of a pressure vessel, fluid-pressure control panel, and electronic equipment. The pressure vessel is connected to the fluid-pressure control panel. A pressure intensifier is used to achieve the required pressure. A rock or soil sample is placed between transducer holders, which are connected to the electronic

equipment. A detailed description of the compressional and shear wave transducer holders used was reported by King (1970).

The ultrasonic wave velocities are obtained by measuring the time taken for a pulse to traverse the length of the specimen. A pulsed oscillator is used to apply a pulse to the transducer, which in turn transmits this pulse through the sample. The electrical signal produced is amplified and displayed on a dual-beam oscilloscope, where the trace of the signal is measured or photographed.

For tests using uniaxial state of stress, samples wre mounted between the plates of the loading frame and the required pressure was applied. For tests using triaxial state of stress, samples were immersed in oil within the triaxial vessel, and samples were loaded using the testing procedure described above.

Natural moisture content, Atterberg limits, and sand-silt-clay ratios were determined according to ASTM standards. All samples were logged and classified using the Unified Soil Classification System. Percentage of visible ice and its distribution also were described and recorded using the permafrost classification of Pihlainen and Johnston (1963).

3.11.3 Testing at CRREL

3.11.3.1 After Nakano and Froula (1973)

Dilatational Waves in Frozen Soils

The dilatational velocities of three standard types of soil -- 20-30 Ottawa sand, Hanover silt, and Goodrich clay (fully water-saturated) -- are presented as a function of temperature in Fig.3.11.3. The measurements were made by one of the pulse-transmission methods based on transmitting a short train of 1-MHz pulses and measuring its first arrival time through the circular cylindrical specimen. The use of suitable electronic devices kept the error in velocity measurements within 1 percent.

It is well known that the frozen soil generally consists of soil mineral (or organic) matter, ice, water (normal water), unfrozen water (interlamellar water), and air. In the pulse-transmission method, the received signal may be considered to be a mixture of waves traveling along various paths through the frozen soil such as the soil mineral-only path and various combinations of the soil constituents. Since the dilatational velocity obtained by the first arrival method depends on the first traveling dilatational wave, it strictly represents the characteristics of the path taken by the first wave. An understanding of the

mechanism of wave propagation is crucial to the interpretation of the velocity data in terms of the physical structure of frozen soil.

In frozen granular soils, such as 20-30 Ottawa sand (Fig.3.11.3a) almost all of the water freezes at the freezing point of water. The dilatational velocity changes suddenly in a stepwise manner at 0°C, and no hysteresis is observed in the velocity during a freeze-thaw cycle. Paterson (1956) showed that, unlike a homogeneous solid in which only two independent disturbances -- the dilatational and shear waves -- could be propagated, porous granular materials could support three waves: two dilatational waves -- one through the mineral skeleton and one through the pore fluid -- and a shear wave through the mineral skeleton. In frozen Ottawa sand, soil together with ice constitutes a mineral skeleton, and all three waves were observed. Actually, the dilatational wave through the pore air travels with the speed of sound in air and can be clearly identified for the frozen Ottawa sand of very little ice content.

Silt and clay have fine pores, in which a significant portion of the water remains unfrozen at subfreezing temperatures. It is evident that a strong correlation exists between dilatational wave velocity and unfrozen water content. The observed hysteresis in the velocity of both Hanover silt (Fig.3.11.3b) and Goodrich clay (Fig.3.11.3c) during a freeze-thaw cycle is considered to be caused by the hysteresis of unfrozen water content.

Since the wavelength of dilatational waves in Hanover silt and Goodrich clay is roughly 10 and 100 times larger than their average grain size, respectively, the mechanism of wave propagation in silt and clay may differ from that in sand, where the wavelength is of the same order as the grain size. It appears that the mixture theory is more appropriate to model this situation than the one applied to granular sand consisting of the mineral skeleton and the pore fluid. To examine further the hysteresis of velocities, an experimental technique was developed to measure wave velocity and unfrozen water content simultaneously.

Kaolinite clay (Kaolinite No.7, Dixie Rubber Pit) was tested under fully water-saturated conditions. The samples were cylindrical disks, 127 mm in diameter by 6.35 mm thick and were sandwiched by two fused quartz plates 127 mm in diameter by 6.35 mm thick.

Measurements of the dilatational wave velocities were made by the pulse-first-arrival method in a refrigerated bath filled with Dow Corning 200 silicone oil used both as a cooling medium and as a

medium for transmitting the input pulses across the soil specimen to the receiver.

The amount of unfrozen water contained in a frozen soil specimen was determined by monitoring the temperature of the specimen and the amount of heat exchanged between the specimen and surrounding silicone oil. The circumference of the specimen was insulated so that heat exchange occurred in the direction perpendicular to the surface of the specimen. Copper-constantan foil thermocouples 5.1 mm thick were attached near the center of both surfaces of the quartz disks to measure the temperature difference across them. A thermocouple also was placed at the center of the specimen to measure its temperature. With this arrangement, it was possible to determine the rate of heat exchange, Q, and the volumetric heat capacity, C, which includes the heat of fusion. The unfrozen water content, w(t), was calculated for each time interval.

In Fig.3.11.4, the dilatational wave velocities are plotted against the unfrozen water content. The relationship between the dilatational velocity and the unfrozen water content can almost be represented by a single curve, regardless of the cycle.

It should be mentioned that in calculating the unfrozen water content, the temperature dependence of the specific heat capacities of clay and water has been neglected. Also, the temperature distribution in the specimen, as well as the nonlinear effect of temperature gradient in quartz disks, was neglected. Although all these factors may add up to a certain amount of error in the final results, there is very little doubt that the unfrozen water content is a major factor contributing to a variation of the dilatational wave velocity with temperature.

Shear Waves in Frozen Soil

Two commonly used pulse-transmission techniques to measure shear wave velocities of earth material are the pulse first arrival method by the use of shear transducers and the critical angle method. The quality of the specimen tends to determine the accuracy of the measurements. In the former method, since the shear wave has an inherently slow velocity, the presence of any component of the faster dilatational wave, whatever its source, tends to obscure the exact onset of th first arrival of the shear wave. Important factors influencing the accuracy of the measurement include coupling between the transducer and the specimen and proper choice of the sensitivity of the receiving transducer.

The critical angle method is based on the elementary theory of critical refraction in a solid.

The shear velocities of three standard types of soils under fully water-saturated conditions were measured by the critical angle method, in which the specimen (114 mm in diameter by 25.4 mm thick) was mounted in the sample holder and was submerged in the tank filled with Dow Corning 200 silicone oil so as to intercept the ultrasonic beam. The surface of the specimen was sealed by a thin vinyl sheet. In practice, the shear critical angle was determined more accurately than the dilatational angle for the frozen soil specimens tested. Also, it was found that the dilatational wave velocities can be determined more accurately than the dilatational angle by measuring the difference in delay time between the pulses received after crossing the liquid path alone as compared with their passage through liquid and specimen interposed at normal incidence.

The shear wave velocity tends to decrease with ascending temperature. The role of unfrozen water in shear wave propagation is not as pronounced as it is on the dilatational wave. Fluid water cannot accommodate shear, and what we consider to be shear wave propagation must result from tortuous solid-only paths and/or multiply converted shear-dilatation motion. In view of the fact that the slope of the velocity-temperature curves does not differ markedly among the tested samples, the soil mineral matrix might play a major role in shear wave propagation. The shear velocities of crystalline rock and polycrystalline ice are about 3.0 and 1.6 km/s, respectively. The measured velocities of frozen soils fall between these two bounds.

3.11.4 Testing at the University of Saskatchewan (After Pandit and King,1978)

(i) Introduction

The authors report on the influence of porewater salinity on some mechanical and electrical properties of porous sedimentary rocks at permafrost temperatures. Ultrasonic velocities were measured as a function of porewater salinity on samples of two sandstones and a limestone under triaxial loading. Complex electrical resistivity and phase-angle

relationships at different frequencies were measured on a sandstone and limestone under hydrostatic loading. All measurements were done in the temperature range of -15°C to 3°C.

(ii) Specimen Preparation

Specimens of 5 cm diameter for the ultrasonic-velocity tests were carefully cored from quarried blocks of Boise and Berea sandstone and Salem limestone, using fresh water as the cooling fluid. The Boise and Berea specimens were cored perpendicular to the bedding. Specimens of 3.8 cm diameter for the electrical resistivity tests were cored from blocks of Boise sandstone and Salem limestone, again using fresh water as the cooling fluid. The flat ends of the specimens were ground perpendicular to the axis of the core and parallel to each other to a tolerance of 0.0015-cm, using fresh water as the coolant. As completed, the ultrasonic velocity specimens were approximately 7.5cm long, and those for the resistivity tests 3.8cm long.

The specimens were dried in a vacuum oven maintained at 105°C under a vacuum of 70 Pa of mercury or lower for at least 24 hours. After weighing, the specimens were saturated in distilled water, 0.03 molar concentration (M) or 0.1 M solutions of NaCl by the following method. They were first saturated by immersion in the saturating solution in a pressure vessel and subjecting them to a vacuum of 270Pa of mercury. To ensure full saturation the immersed specimens were then pressurized to 10MPa.

The 5cm-diameter specimens were mounted in turn between piezo-electric transducer holders for ultrasonic-velocity tests. Lead foil discs of 0.0006cm thickness provided acoustic coupling at each transducer holder. Each specimen was surrounded by double jackets of tightly-fitting, thin rubber, over which overlapping vinyl tape was wrapped. This ensured that the DC 200 silicone fluid exerting the confining pressure did not invade the specimen pore space. The 3.8cm-diameter specimens for the resistivity tests were mounted between electrode holders in the same manner, except that a thin layer of graphite on the electrodes provided electrical coupling.

(iii) Apparatus

A block diagram of the ultrasonic-velocity apparatus is shown in Fig.3.11.5. The piezo-electric transducer holders are designed

to measure compressional and shear-wave velocities sequentially on the same specimen, and are similar to those described by King (1970). The specimen is surrounded in the triaxial cell by DC 100 silicone fluid. Compressed nitrogen is employed to apply the confining pressure and axial stress on the specimen. Pore-fluid ports permit free drainage of the pore fluid from the specimen. Ultrasonic velocities can be measured with an accuracy of ±1 percent and with a precision of ±0.5 percent on a given specimen.

The controlled-temperature chamber can be maintained at temperatures in the range of -18°C to 21°C, within the limits ±0.05°C. Temperatures in the chamber and within the pressure cells in the DC 200 silicone fluid adjacent to the specimen are monitored by platinum resistance sensors.

A block diagram of the electrical-resistivity apparatus is shown in Fig.3.11.6. A phasemeter is employed to measure phase-angle relationships. Pore fluid ports permit free drainage of the pore fluid from the specimen. Preliminary tests on the system with hollow cardboard cylinders surrounded by rubber jackets and the DC 200 silicone fluid, and with different values of precision resistors placed between the electrode holders to simulate a resistive specimen, indicated no inductive coupling in the frequency range 5Hz to 10kHz. Tests with water-saturated cylinders of permafrost of different lengths in the range 3.8cm to 7.6cm indicated the presence of measurable contact resistance only in the frequency range 5Hz to 100Hz at temperatures below -8°C.

(iv) Procedure

The operational procedure for both ultrasonic-velocity and electrical-resistivity tests is similar. Specimens mounted between the ultrasonic transducer holders and resistivity electrode holders in their respective pressure cells are placed in the test chamber maintained at room temperature. The specimens are then subjected to a confining pressure of 0.1MPa. After all pressure and electrical connections have been tested, preliminary ultrasonic-velocity and resistivity measurements are made at room temperature.

The temperature in the test chamber is then reduced to -15°C, with the specimen continuously subjected to a confining pressure of 0.1MPa. The time required for a specimen to come to equilibrium with its surroundings at this temperature has been experimentally demonstrated to take several hours. No measurements are made, therefore, until 24 hours have elapsed with the temperature of the chamber maintained at this level.

Ultrasonic-velocity and resistivity measurements are made at the lowest temperature. These are followed by measurements made at successively higher temperatures, allowing the specimens to come to thermal equilibrium with their surroundings for 24 hours at each temperature step.

For the ultrasonic-velocity tests each specimen was first subjected to a hydrostatic pressure of 0.35MPa. The axial stress was then raised in five steps to a maximum of 13.8MPa, with compressional and shear-wave velocities measured at each step in axial stress. Between runs, while the chamber temperature was being changed to a new level, the confining pressure on the specimen was reduced to and maintained at 0.1MPa.

For the electrical-resistivity tests each specimen was subjected to a hydrostatic pressure of 0.35MPa while complex resistivity and phase-angle measurements were being made. Between runs, the confining pressure on the specimen was reduced to and maintained at 0.1MPa.

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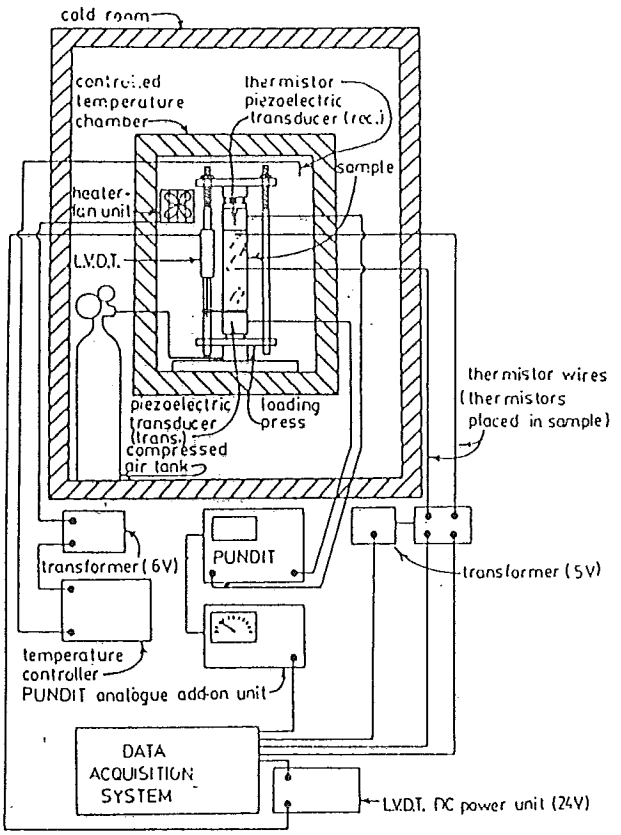

FIGURE 3.11.1 Laboratory Equipment Set-Up (after Fransham et al, 1982)

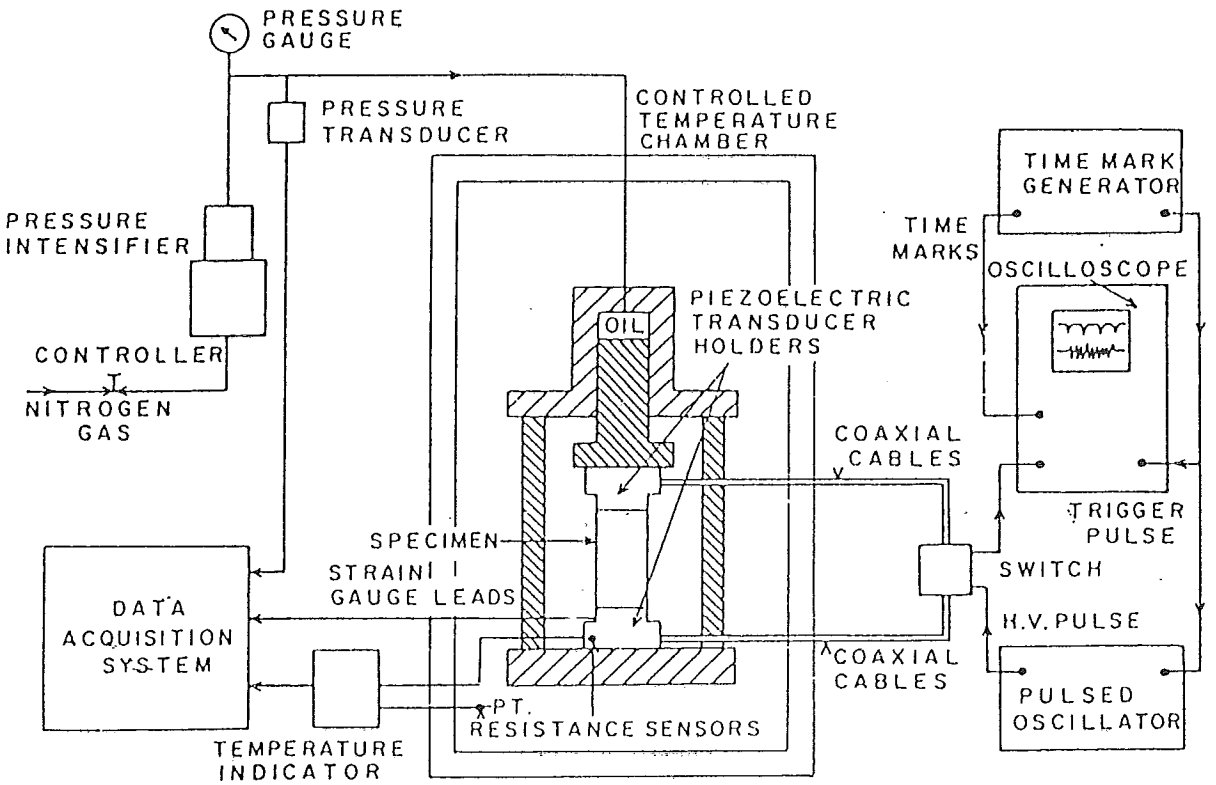

FIGURE 3.11.2 Block Diagram of Acoustic Velocity Apparatus (after Kurfurst, 1976)

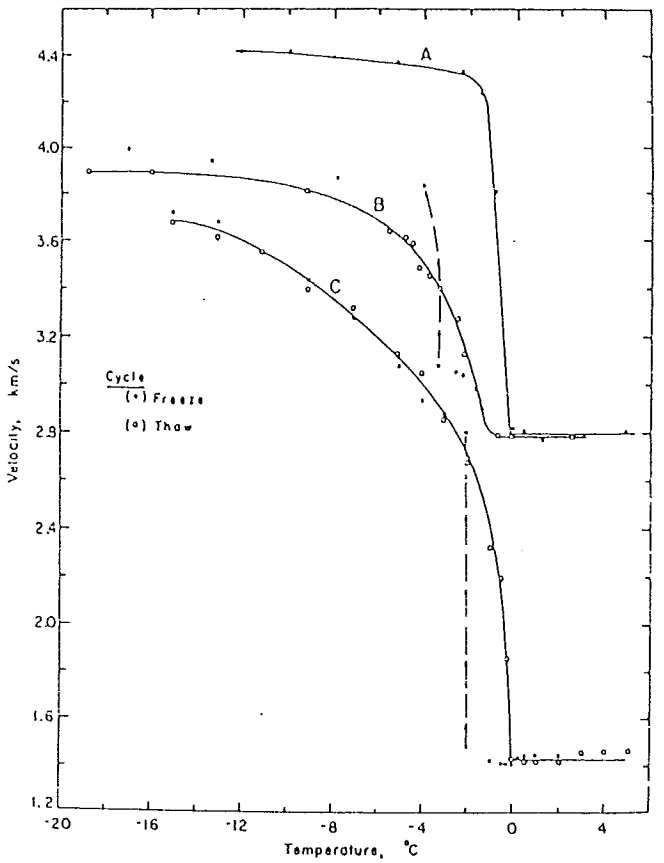

FIGURE 3.11.3 The dilatational wave velocity versus temperature for

a) 20-30 Ottawa sand, wet density p = 2.20 g/cm^3
b) Hanover silt, p = 1.83 g/cm^3
c) Goodrich clay, p = 1.80 g/cm^3 under fully water-saturated conditions.

Notice the discrepancy between the freezing and thawing cycles for B and C. No discrepancy was observed for Ottawa sand.
(after Nakano and Froula, 1973)

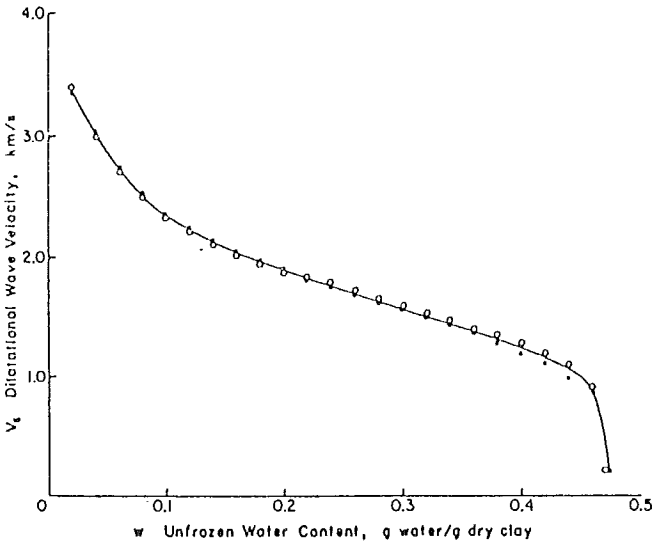

FIGURE 3.11.4 Dilatational velocity vs. unfrozen water content. The solid circles indicate the colling cycle; the open circles, the heating cycle. (after Nakano and Froula, 1973)

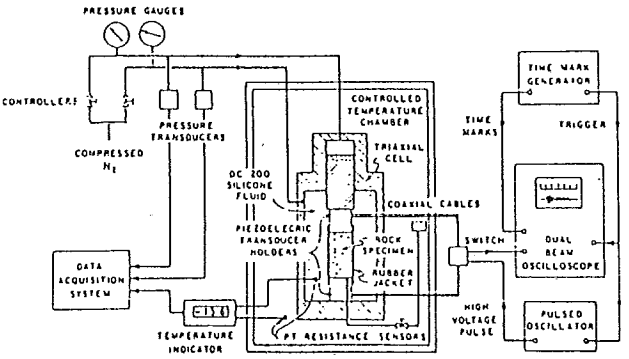

FIGURE 3.11.5 Block Diagram of Ultrasonic-Velocity Apparatus (after Pandit and King, 1978)

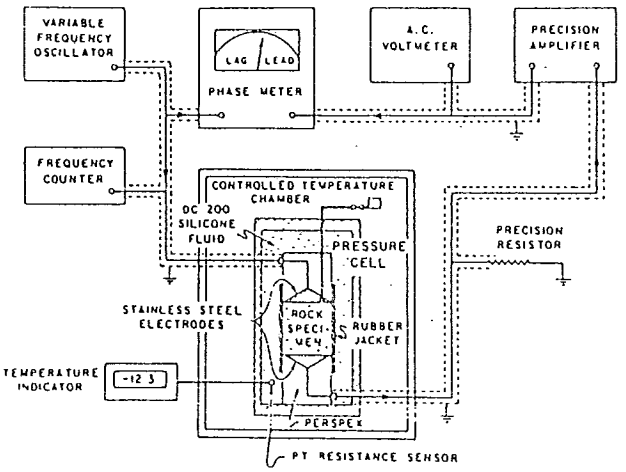

FIGURE 3.11.6 Block Diagram of Electrical-Resistivity Apparatus.
(after Pandit and King, 1978)

3.12 HYDRAULIC CONDUCTIVITY TESTS

3.12.1 Introduction

The measurement of the hydraulic conductivity of frozen soils is often made in conjunction with consolidation and frost-susceptibility tests. However, several authors have developed procedures for the measurement of permeability alone. These procedures are variations on the well-known constant head (ASTM D2434) and falling head permeabilitiy tests, for which procedures are given by Bowles (1970).

3.12.2 Hydraulic Conductivity Test Developed at Carleton University, Ottawa

A procedure for the measurement of the hydraulic conductivity of frozen soil samples was developed at Carleton University, and is described by Williams and Burt (1974) and Burt and Williams (1976). The water contains dissolved lactose, so that it remains unfrozen while passing through frozen soil samples.

Apparatus and Procedures (Burt and Williams, 1976)

Figure 3.12.1 shows the apparatus used to determine the hydraulic conductivity of frozen soil samples. It is essentially similar to that required to measure the hydraulic conductivity of a saturated unfrozen sample. The sample (3 cm long, 1.9 cm rad) is frozen and placed between two reservoirs which are then filled with lactose solution (see (ii) below). A hydraulic gradient is established across the system by applying pressure to one reservoir, and flow occurs. The discharge is measured in a capillary tube. Certain modifications are required because of the presence of frozen sample:

(i) The sample and reservoirs are maintained at freezing temperatures by immersion in a bath of ice and lactose solution, the concentration of which is adjusted to give the desired temperature.

(ii) The unfrozen water in the frozen soil possesses a negative pore water pressure, or suction. If pure water was placed in the reservoirs, even if it did not freeze, there would exist a

tendency for water to be pulled into the sample from both sides. The presence of lactose in the reservoirs however serves to equalize the potentials in the reservoir and in the soil water. The lactose solution used is of the same concentration as that in the ice bath. The lactose solution in the bath is in equilibrium with pure bulk ice. The unfrozen soil water and the soil ice (essentially pure, and in bulk i.e. lenses) are also in equilibrium. As the temperatures are equal throughout it follows that the unfrozen soil water and the lactose solution are in equilibrium. For each temperature at which a measurement is made, the reservoirs are refilled with the lactose solution from the ice bath. The lactose solution of course also obviates ice formation in the reservoirs.
(iii) The presence of lactose in the reservoirs creates the possibility of lactose molecules moving into the soil, either by molecular diffusion or by being transported by the flowing water. A dialysis membrane is therefore fitted on each end of the sample; this restricts entry of lactose, although lactose molecules still move into the sample gradually (considered further, below).

The normal practice used for testing the hydraulic conductivity of a frozen soil sample was to start with the ice bath at its coldest (concentrated lactose solution) and to allow the sample to gradually warm up, making observations of flow at as many temperatures as possible. The gradual melting of ice and consequent dilution of the lactose solution causes the equilibrium temperature of the ice-lactose solution mixture to rise towards $0^{o}C$. It is possible instead to cool the sample by additon of ice and lactose to the ice bath, but this was found practicable only for lowering the temperature by about $0.1^{o}C$.

Burt and Williams (1976) observed several problems with their experimental procedure:

(i) The dissolved lactose lowered the freezing point of the water in the soil, as well as inducing an osmotic potential which lowered the total soil-water potential. This caused thawing and a rise in permeability at the thawed end of the sample. The effects on the overall permeability of the sample were shown to be minimal by using dissolved polyethylene glycol in place of lactose. However, the frozen sample length should be corrected for the existence of the thawed layer.

(ii) Even very concentrated lactose solutions freeze at about -10°C, making measurements at lower temperatures difficult. However, lactose solutions may be used at lower temperatures than other solutions, e.g. sodium chloride.

(iii) The test procedure assumes a constant head for the duration of the test. A substantial drop in head was observed after several hours in tests on some clay samples, with no apparent explanation.

(iv) Large heads are required to produce a measurable flow in some samples. This produced some thawing due to freezing point depression.

3.12.3 Tests at University of Alberta

Roggensack (1977) obtained permeability data on thawing clay samples from the results of consolidation (oedometer) tests. This data was checked by conducting constant head permeability tests directly on the oedometer sample after consolidation. The apparatus used is shown in Fig.3.12.2. Additional checks on permeability were made by falling-head tests.

3.12.4 Hydraulic Conductivity Measurements at CRREL

A pressure cell permeameter apparatus has been developed at the CRREL laboratories for the measure of hydraulic conductivity and moisture-tension characteristics of frozen soils (Ingersoll, 1981). The apparatus and procedure are described in detail in Section 3.6.2.4 of this report.

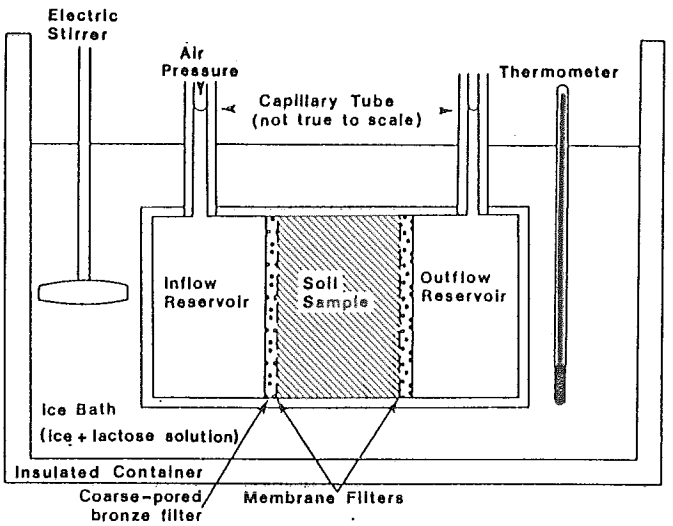

FIGURE 3.12.1 Diagram of Apparatus Used to Measure Hydraulic Conductivity of a Frozen Sample (after Burt and Williams, 1976)

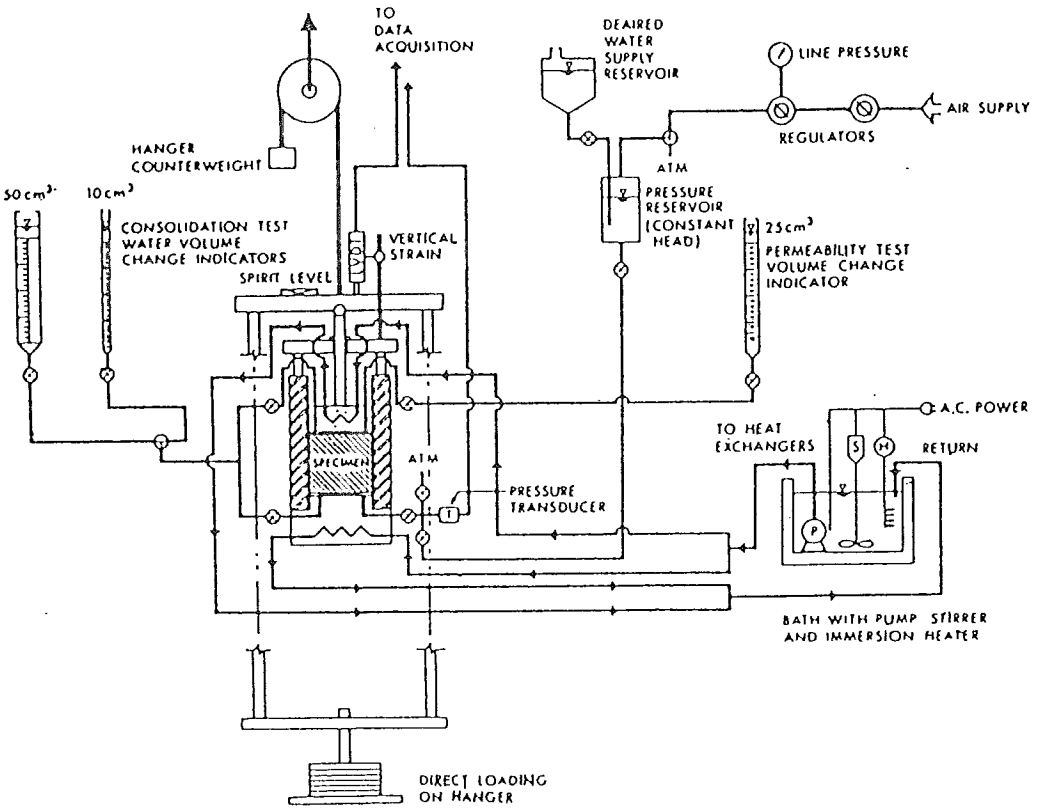

FIGURE 3.12.2 Schematic Layout of Permode and Associated Apparatus Used in Residual Stress, Thaw-Consolidation and Conventional Consolidation Tests (after Roggensack, 1977)

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APPENDIX A

CASE HISTORIES OF DRILLING AND SAMPLING FROM PUBLISHED LITERATURE

CORING METHODS

METHOD OF DRILLING	TYPE OF CORE BARREL			REFRIGERANT		SEASON	MATERIALS MOST SUITABLE FOR SAMPLING	SAMPLE QUALITY	TYPES OF LAB TESTS RECOMMENDED	REF. NO.	COMMENTS
	NAME	ϕ	BIT TYPE	TYPE	TEMP. RANGE						
Franks Model FA-11 Truck Mounted Drill	double-tube, swivel-head	M and NXM	(A) Steel, bottom discharge (B) Tungsten carbide, bottom discharge (C) Diamond, bottom discharge	(1) Compressed Air (2) Fresh Water (3) Brine (4) Artic Grade Fuel Oil DF-A (5) Drilling Mud		Preferably in Winter and early Spring	(A) Ice and snow (B) & (E) frozen, fine and medium grained soils (C) gravelly soils and coarse tills	A & B; Satisfactory C; Fairly good, but broken core D; Poor quality E; Often broken and partly thawed core F; Good cores in hard frozen soils G; Relatively good, but surface contamination		C1 (Hvorslev & Goode)	1. Water tends too freeze. 2. Sodium Chloride preferable to calcium chloride for brine. 3. F G & H must be cooled below 0°C.
Failing - 1500 drill rig			Drag and rock bits	Refrigerated Diesel Fuel		Any season	Frozen silts and sands, frozen gravel and sandy gravel	Contaminated		R1 (Lange)	Good recovery
				Compressed Air		Not recommended for warm weather					Poor recovery
NC continuous wireline	double-tube, swivel-type	2-3/4	Both internal and bottom discharge diamond	Diesel Fuel				Absorbed considerable diesel fuel	Liquid contents,	R1 (Lange)	85-90% recovery
Concore A5 Junior (portable)	single-wall core barrel	2½"	tungsten carbide saw-tooth (Wyr-lok)	Compressed Air		Spring	Silts and ice wedge ice	Physically and chemically undisturbed		R1 (Brown & Sellman)	Drilling confined to upper 5 ft of of permafrost.

CORING METHODS

METHOD OF DRILLING	TYPE OF CORE BARREL			REFRIGERANT		SEASON	MATERIALS MOST SUITABLE FOR SAMPLING	SAMPLE QUALITY	TYPES OF LAB TESTS RECOMMENDED	REF. NO.	COMMENTS
	NAME	ϕ	BIT TYPE	TYPE	TEMP. RANGE						
Failing 314 rotary rig	DCDMA 4x5½ in. core barrels, 20 ft long fitted with sludge barrels	4 x 5½" in.	Five bit types; B-413-A, B-413-B B-413-C B-413-D B-413-DA, all ice coring bits (fairly soft 4140 and 1020 steel)	Compressed Air			Ice	Core quality ranges from excellent to unusable.		DI (Iange)	1. 3 types of core lifters employed 2. Core generally in good condition, except where damaged or lost because of lifter failure 3. Better core might have been obtained if rotation of the core barrel could have been steadied. 4. A few circulation problems.
			Same as above only bits had more curved cutting edges					Improvement in core quality due to new bit design and use of drill collar			1. Larger quantities of excellent core obtained.
								Most good quality fewer cracks in core when diesel was used on short run			1. 98% recovery 2. Use of constant core feed device improved coring. 3. Author suggests diesel may greatly improve core quality and depth limit of equipment.

CORING METHODS

METHOD OF DRILLING	TYPE OF CORE BARREL			REFRIGERANT		SEASON	MATERIALS MOST SUITABLE FOR SAMPLING	SAMPLE QUALITY	TYPES OF LAB TESTS RECOMMENDED	REF. NO.	COMMENTS
	NAME	ϕ	BIT TYPE	TYPE	TEMP. RANGE						
Mayhew 200 rotary drill rig	Shelby tube (used as rotary core barrel)	2.5'	tungsten carbide teeth 2 teeth	Air (-3^{o} to -6^{o}C)		Spring		Unsatisfactory core, many breaks Uncontaminated	Moisture content, grain size, isotopic and chemical analyses and radio carbon dating	07 (Lawson & Brockett)	1. Poor retrieval
	"	"	tungsten carbide teeth 4 teeth	"			Ice-rich sediments and massive ice, fine-grained	Quality of core varied, uncontaminated			Good retrieval
	double walled core barrel	NXHW	tungsten carbide tips; 3 types-internal discharge, clay bit, and face discharge	Air							None of the bits obtained core, and only the internal discharge bit cut a core in massive ice.
Failing Model 1500 SS (trailer mounted)	DCDMA large series, 5 ft.		Diamond, bottom discharge	Diesel fuel (with small amount of Baragel)			Frozen sand and sandy gravel	Good core		12 (Lange)	~85-100% recovery
			V contour bit, internal discharge					Good core, some cobbles torn from core			"
			Ribbed internal discharge diamond					Some tearing of gravel from core			"
			Diamond core bit, bottom discharge	Compressed Air		Not warm weather					Unsuccessful due to problems with air circulation.

CORING METHODS

METHOD OF DRILLING	TYPE OF CORE BARREL			REFRIGERANT		SEASON	MATERIALS MOST SUITABLE FOR SAMPLING	SAMPLE QUALITY	TYPES OF LAB TESTS RECOMMENDED	REF. NO.	COMMENTS
	NAME	ϕ	BIT TYPE	TYPE	TEMP. RANGE						
Failing Model 1500 SS (trailer mounted)			Diamond bit, internal discharge	Compressed Air		Not warm weather	Sand and little gravel	Good core		12 (Lange)	85-100% recovery, still plugging of bit.
	DCDMA large series, 5 ft.	2-3/4" x 3-7/8"	bottom discharge full round, crown	Diesel fuel			Frozen, badly fractured bedrock	Excellent core			?
Longyear Straight line Diamond Core Drill - Model UG8	Single tube barrel to 5 or 6', then double tube barrel	7"OD x 6" ID single and double tube	2 5/8" chuck, saw-tooth bits	Ice cooled water was used during periods of warm weather			Frozen silt			S5 (Davis & Kitze)	1. Good sample recovery due to control of wash water. 2. Alcohol used to keep drill rods from freezing.
Acker Teredo Core Drill-Type TH	double tube core barrel	Size NX, "L" type 5 ft long core catcher	Hard surfaced saw tooth bit	?			Frozen fine-grained soils				1. Recovery better than 90%. 2. Not effective in frozen gravel, may be better if casing and diamond bit were used
Chicago Pneumatic Core Drill - Model 8	A Acker split tube and solid tube single and double tube B Chicago Pneumatic thin wall samplers	A 2½" OD and 2" OD B 2" and 2½" OD	?	?						S5 (Davis & Kitze)	1. Sample recovery was very good to excellent.
Concore Drill type E5-48	double tube	NX 5 ft long		Water			Silty material	Cores had a tendency to melt		S5 (Davis & Kitze)	1. Core recovery very good.

DRIVE SAMPLING

METHOD OF DRILLING	DRIVE SAMPLING		SEASON	SUITABLE MATERIALS	SAMPLE QUALITY	RECOMMENDED LAB TESTS	REF. NO.	COMMENTS
	TUBE ϕ	WALL THICK-NESS						
Acker Teredo Core Drill	Acker solid tube (3" ID)	3/16"	Late winter and early spring	Frozen silt soil				1. Recovery ~ 95%. 2. Driven with 750 lb hammer, 18-24 in drop. 3. Tube failure
	Acker split tube sampler (1½" ID)	0.25"						1. Effective with 350 lb hammer, 18 in drops. 2. Unsuccessful with 16 lb sledge hammer.
Cyclone churn drill	Steel pipe (3" ID) with core catchers	1/8"		Frozen and unfrozen silt soil	Disturbance of soil structure	Moisture contents and other standard soil classification tests except density determination		1. Driven with 750 lb hammer, 18-24 in drops. 2. Approx. 100% recovery.
Acker Core Drill (350 lb hammer, 18 in drop)	Sprague & Henwood solid tube and split tube (2.5" ID)	1/4"					S5 (Davis & Kitze)	1. No penetration, wall thickness too great.
10 lb sledge hammer	Electrical conduit sampler (1.6" ID)	0.065"	Summer					1. Impossible to drive in winter. 2. Satisfactory in summer.
Acker drill tripod arrangement (350 lb hammer, 12-18" drops)	Shelby Tubes (2" OD)	1/16" and 1/8"		Frozen silty soils				1. Square cut end satisfactory.
10 lb sledge hammer								1. Sampled to 16 ft, 12 ft into permafrost

AUGERING/CHIP SAMPLES

METHOD OF DRILLING	TYPES OF AUGERING OR DISTURBED SAMPLES	SEASON	SUITABLE MATERIALS	TYPE OF LAB TEST RECOMMENDED	REF. NO.	COMMENTS
Winkie GW10 and GW15 drill (JK Smit)	Unsuccessful				P7 (Isaacs & Code)	Equipment too small.
Hand-driven coring tool, small and large rotary drills	USA-CRREL ice-coring augers in various diameters (11.3 cm OD - 3.8 cm OD)		Snow, ice, and fine-grained organic and mineral soils.		P5 (Veillette & Nixon)	1. Small dia. augers designed for use with motorized power sources. 2. Augers often jam on cuttings. 3. Soils containing a significant amount of unfrozen water are unfavourable.
Haynes model 500 earth drill, using CRREL barrels	Unsuccessful in ice-rich varved clay due to high rotational speeds, lower speeds are more successful		Any frozen soil except extremely gravelly or stony ones			1. Portable power augers should have: 1. low boring spindle speed, 2. sufficient torque (350 ft. lb), 2. Clean ice, sand with pore ice only, silts, and soils with 75% or more ice by volume have best penetration rates
General Equipment digger model 51 and Stihl 4308 auger, both with CRREL barrels						
Failing Model 43 SA rotary rig	3" Coalmaster, 2-pt. cutter					Adequate penetration
	3½" Kamo, 2 bladed-cutter					
	3½" Kamo, with 2 chippers				R4 (Lange)	Not suitable for rocky soil, teeth too slender, broke several
	6" Coalmaster with 9 teeth					Unsuccessful

METHOD OF DRILLING	TYPES OF AUGERING OR DISTURBED SAMPLES	SEASON	SUITABLE MATERIALS	TYPE OF LAB TEST RECOMMENDED	REF. NO.	COMMENTS
Failing Model 43 SA rotary rig	6" Kamo with teeth and blade				R4 (Lange)	r.p.m. over 120 causes teeth aid blade failure
	6½" Kamo, 2½" cutters with small pilot					Best cutter in gravelly material in this group.
	6" Coalmaster, 9 short teeth					Rugged bit

CORING METHODS

METHOD OF DRILLING	TYPE OF CORE BARREL			REFRIGERANT		SEASON	MATERIALS MOST SUITABLE FOR SAMPLING	SAMPLE QUALITY	TYPES OF LAB TESTS RECOMMENDED	REF. NO.	COMMENTS
	NAME	ϕ	BIT TYPE	TYPE	TEMP. RANGE						
Boyles Bros. 17A diamond drill - wireline capability	Long-year (03-Series) triple tube split inner tube 5ft long	HQ	face discharge diamond	Thermal 55	(± 1°F)			High	thermal conductivity, diffusivity, specific heat, water contents, and bulk densities	P7. (Isaacs & Code)	1. Long year hydraulic head-diesel powered. 2. 97-100% core recovery.
				Artic Grade Diesel Fuel				Surface Contamination			
Winkie GW/D and GW15 drills (J.K. Smit)	Double-tube swivel-type, 5ft long	NX	face discharge	Fresh Water						P7 (Isaacs & Code)	1. Poor recovery.
	Swivel-type triple-tube	NV-3	face discharge	Fresh Water							1. 90-95% recovery. 2. Low productivity.
Winter Weiss Mayhew top-drive rotary drill	Mayhew double-tube floating	2-3/4"	drag tooth 8 - tooth drag tooth 4 - tooth	Cooled air (rate of 75 c.f.m. at 40 psi		Preferably Winter temp. less than 10°F	Frozen sand (have problems in frozen clays)		thermal conductivity	P7 (Isaacs & Code)	1. 8-tooth bit caused melting and freezing problems. 2. Best results when air temp. below 0° F. 3. Carbide bit teeth chipped in pebbly layers.
Failing 43-SA rotary type drill rig	Single-wall, concrete type	2-3/4" x 3-7/8"	tungsten-carbide bit (Wyrlok)	Naturally refrigerated compressed air		Spring				C2 (Sellmann & Brown)	1. Employed only in upper meter, to get starter hole.
	Double tube, large series, swivel type		Drag bit, saw-tooth arrangement 5 or 6 teeth of tungsten-carbide				1. Sandy silt with M.C. of 20% 2. Core could be recovered in ice-cemented gravel	No attempt was made to keep core thermally undisturbed during coring, but core was chemically uncontaminated			1. Six-tooth arrangement gave best performance. 2. Coring not possible whe ambients rose above -6°C because of problems with air 3. Core recovery ~ 98%. 4. Greatest core losses in gravel and loose sand.

DRIVE SAMPLING

METHOD OF DRILLING	DRIVE SAMPLING		SEASON	SUITABLE MATERIALS	SAMPLE QUALITY	RECOMMENDED LAB TESTS	REF. NO.	COMMENTS
	TUBE ϕ	WALL THICK-NESS						
Boyles Bros. 17A diamond drill	Shelby	thin wall		Unfrozen clay		Thermal conductivity, diffusion, volumetic specific heat, water contents, and bulk densities	P7 (Isaacs & Code)	Tubes damaged in ice lenses.
Lightweight aluminium derrick, with motorized hoist	Split - spoon				Superior samples, as water was not used			High productivity with small operating crew.
Acker portable drive sampling drill (63.5 Kg drop hammer)	Split tube (5.1 cm OD)		South of -5°C ground isotherm (northern limit)	Clay, silty clay, clayey till	Usually of good quality, slightly disturbed	Liquid and plastic Atterberg limits, grain size distribution, and natural water content	P5 (Veillette & Nixon)	1. Recovery often close to 100%. 2. Silty sands or sand at -5°C or lower cause excessive wear on equipment
	Lynac sampler	thickened head section						Better for slow penetration and (prolonged pounding).
Helicopter portable rotary drill	(5.1 cm OD) split tube				Highly fractured core			1. Very slow penetration and prolonged hammering. 2. Thought to be too far north.
Thor, Size 12 pavement breaker	Shelby Tubes (1 1/8" OD)	1/8"		Frozen silty soils			S5 (Davis & Kitze)	1. Effective
Hvorslev Sampler (T-handle)	6 in. tube with 1.87" ID			Thawed soils				Inadequate for permafrost.

APPENDIX B

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