CRYOGENIC ALTERATION OF CLAY AND SILT SOIL MICROSTRUCTURE
IMPLICATIONS FOR GEOTECHNICAL PROPERTIES

by

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Department of Earth Sciences

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Abstract

Micromorphology and computer image analysis techniques, together with testing of geotechnical properties of clay and silt soils exposed to between one to ten freeze-thaw cycles, revealed evidence of reorganisation of soil fabric components and pore space. Fragnoidic, fragmic, fragmic-porphyskelic and banded-porphyskelic fabric types were observed to develop in response to cryogenic alteration of granoidic-porphyskelic and porphyskelic fabrics created by compaction. The resulting morphology was observed to be responsible for up to two orders of magnitude increases in hydraulic conductivity in soils characterised by fragnoidic fabric, and up to an order of magnitude increase where fragmic and banded porphyskelic fabric types were observed to have developed. Conversely, one order of magnitude decrease in hydraulic conductivity was observed in soils where porphyskelic fabric types had developed.

Computer image analysis observations revealed that macroporosity accounted for between 35 to 78% of sample porosity for soils characterised by fragnoidic fabric, 25 to 55% of the porosity of fragmic and banded-porphyskelic fabrics, and for between 12 to 36% of the porosity in soils characterised by a porphyskelic fabric.

Cryogenic alteration of the soil morphology resulted in changes to hydraulic conductivity, porosity and water reten-

tion after only one freeze-thaw cycle. The larger increases in soil porosity and water retention were observed to occur between one to three freeze-thaw cycles and between two to five freeze-thaw cycles for hydraulic conductivity.

The extent to which soil microstructure and geotechnical properties undergo cryogenic alteration from one freeze-thaw cycle to the next has provided valuable insights into the complexities which exist in the mechanics of frost heave and consolidation. Ice lens formation and cryosuction are responsible for the development of these cryogenic fabrics with their inherent differences in hydraulic conductivity, porosity and water retention.

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Author's Note

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CHAPTER 1

Introduction

1.1 Subject and framework

Frost action, the annual frost heaving and thaw weakening of surficial soils is common throughout much of Canada during the winter months. Annually, differential movement of frost heave susceptible soils which generally goes unnoticed is responsible for damage suffered by much of Canada's infrastructure. The extent to which roads, sewers, water lines and pipelines are damaged each winter and spring reveals a weakness inherent in engineering approaches to design and in construction practices. In economic terms, repair and rehabilitation programs now account for 30% of most Canadian municipalities' annual budgets.

In the mid 1980's the Federation of Canadian Municipalities (FCM 1985) documented concerns of both politicians and

public works managers of 98 communities with respect to ageing facilities that were gradually but inevitably deteriorating. In December 1989 Ontario's Auditor General observed that since 1979 the percentage of the province's highways rated as poor or substandard had risen from less than 40 percent to more than 60 percent (Magill, 1991). A 1992 follow up study (FCM 1994) indicates that spending on municipal infrastructure did increase significantly in the latter half of the 1980's and that a capital expenditure of 14.5 billion dollars was now required to return Canada's municipal infrastructure to acceptable conditions.

Clearly a better understanding of the interaction between frost heave susceptible soils and the aging infrastructure of Canada's municipalities, specifically when subjected to freeze-thaw cycling would help to improve our cold climate engineering acumen.

Perhaps the most common evidence of frost action is the annual heaving that occurs to the surfaces of roads during the winter. This heaving represents one of the most fundamental characteristics of frost heave, namely, the formation of segregated ice lenses, and the accumulation of this segregated ice over the course of a winter in fine-grained soils. Ice segregation is responsible for increases in the soil volume which are greater than can be accounted for by the volumetric expansion of water in soil pores when it changes phase to become ice. Ice segregation occurs in

soils when chemical potential becomes imbalanced in the region of ice lens formation. This imbalance causes soil water to flow toward the growing ice lenses (Figure 1.1). For several decades soil scientists and engineers have carried out studies on the nature of frost action. Their research has yielded a great deal of information on the general effects of freezing of surficial soils, their susceptibility to heave and the fundamental role of ice segregation.

Unfortunately some sixty years after the publication of the classic works of Taber (1929), Casagrande (1931) and Beskow (1935) we still find ourselves lacking a reliable test method by which scientists and engineers can properly assess a soil's susceptibility to heave. Over the course of the last sixty years of research on this subject, more than one hundred methods have been proposed since Taber's treatise (1929) on the mechanism of ice segregation in soils and Casagrande's frost heave criteria (1931). Casagrande observed that under natural freezing conditions with sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than 3 per cent of grains smaller than 0.02 mm, and in very uniform soils containing more than 10 per cent smaller than 0.02 mm. Even though there has been almost continuous research on frost heave and to a more limited degree thaw consolidation, Casagrande's criteria are still the most successful when

Figure 1.1: Ice lens formation

Modified from: B. Van Vliet-Lanöe, 1985, p. 118.

trying to predict a soil's susceptibility to frost heave, in spite of the probability that he never intended that these criteria be universally applied (Chamberlain, 1981).

In today's research programs an emphasis is being placed on computer modelling of frost heave. Concurrent with this approach, various assumptions and approaches that different models make are being reviewed in order to arrive at a more reliable means by which researchers can predict frost heave. At the same time, small and large scale physical modelling of frost heave is being conducted. Apparatus very similar to that of Taber's original setup is being used to conduct detailed small scale frost heave experiments. Full scale frost heave experiments have been conducted in large scale test facilities located in France and Japan. Detailed laboratory experiments are also being conducted in order to gain greater insight into the nature of moisture movement in response to various temperature gradients and hydraulic gradients that it is envisaged take place in the frozen fringe.

This thesis reports the findings from a path of research which was conducted using both small scale frost heave modelling and full-scale ground freezing experiments. Whereas the general effects of freezing of surficial soils are fairly well known and continue to be studied, this thesis examines the cryogenic alteration of clay and silt microstructure and changes to geotechnical properties such

as hydraulic conductivity and porosity which affect the frost heave characteristics of soils.

1.2 Historical perspective of frost action

During the development of stage coach routes throughout northern Europe in the 1700's and in North America in the 1800's it was observed that frost heaving was responsible for damages suffered by road surfaces, culverts and bridge piers. Observations that the disturbances of soil due to freezing are probably as old as the network of Roman roads which were established 2,000 years ago in northern Europe and England. In his classic research paper published in 1935, Beskow states that early Swedish literature indicated that people in Sweden understood that frost caused the uplift of boulders in fields. This phenomenon was described in 1644 by Hiarne who said "...in fields where boulders have been picked out and the land cleared, more boulders will be generated...". In 1765 Runeberg concluded that frost heave associated with ground freezing was due to the volume change (approximately nine per cent volume increase) which accompanied the phase change of the water held in soil pores to ice. Runeberg also reported the presence of bands of clear ice in frozen soil and that beneath the frozen soil ice granules could be found surrounded by unfrozen soil. The Runeberg concept that heaving was due to the expansion of

the pore water in the soil upon freezing was retained until the early 1900's.

In 1897 Holinquist observed that in clay-rich soils the soil between the lower ice lenses was often unfrozen. This observation led to the conclusion that a lower freezing point resulted from the withdrawal of pore water from this zone of unfrozen soil by the overlying layer of ice. This observation was followed by extensive studies of the freezing point in soil. From 1914 to 1923 Bouyoucos observed that marked differences in the freezing point existed for different soils at different moisture contents. Johansson's experimental results (1914) showed that during the freezing of fine-grained soils, water flows to the freezing layers and that this resulted in increases to the water content of these layers. The combined findings of Holinquist, Bouyoucos and Johansson were responsible for the formation of Taber's concept of water continuing to flow to sites of ice nucleation until ice crystals had developed into ice lenses.

Taber's review of Becker and Day's work (1905) on crystal growth in saturated solutions revealed that the expansion of water due to freezing is not the fundamental cause of heaving and that heaving was actually attributed to the formation of ice lenses. Becker and Day had observed that the growth of a crystalline aluminum was capable of raising a kilogram weight several tenths of a millimetre. In 1918 Taber proved experimentally that ice forming in clay

soils could also lift weights. The comprehensive report of Taber's research published in 1929 not only confirmed the validity of these earlier conclusions but also gave the range of conditions under which ice lenses form.

Beskow's classic monograph (1935) reinforced and greatly extended Taber's research efforts on the mechanics of frost heaving and continued to contribute to a better understanding of frost heave for various soil types under different moisture and temperature regimes throughout much of the 1940's.

Throughout the 1950's geotechnical engineers and soil scientists concentrated their efforts on developing variations of the same frost heave apparatus utilised by Taber and carrying out frost heave tests on a wide range of soil types. In spite of their efforts a clearly defined correlation between frost heave of soils and engineering properties remained elusive. This decade of research did however yield works by Jackson and Chalmers (1958) in which the mechanism of heaving was attributed to the kinetics of solidification while Gold (1957) suggested it was based upon the surface tension of the ice / water interface. Cass and Miller et al. (1960) suggested a role for the osmotic properties of diffuse electrical double layers on the soil grain surfaces.

The 1960's ushered in a decade of advancements in the understanding of frost heave, freeze-thaw characteristics of colloidal and colloid-free soils, the introduction of the

phenomenon known as thermally induced regelation (Hoekstra and Miller, 1967) and to the discovery (Dirksen and Miller, 1966) that freezing-induced redistribution of water in moist soils exceeded, by orders of magnitude, the amount that could be explained by the otherwise successful theory of thermally induced redistribution of moisture in porous media (Phillip and DeVries, 1957). In 1961 Everett introduced the classic ice-segregation model based on the relationship of $P_i - P_w$ (pressure difference) present at the ice - water interface. Williams (1968) shed more light on the characteristic behaviour and properties of frozen soils and attributed the unique nature of the properties to the co-existence of ice and water under conditions imposed by the porous structure of the soil. A clear relationship between pore size and freezing temperatures and their correlation to pressure was also revealed by Williams (1967). Hoekskra (1966) advanced our understanding of diffusion processes in the frozen soil and began to incorporate concepts of irreversible thermodynamics.

Further studies of the general processes involved in heat and mass transfer in soil appears to have been the main focus of research carried out in the 1970's. Radd and Oertle (1973) conducted a series of frost heave experiments that demonstrated a Clapeyron-type of pressure and temperature relationship existed in freezing soils. Burt and Williams (1976) demonstrated that unfrozen water contained

in small capillaries as films adsorbed on surface of soil particles is mobile, and that as the temperature of the soil falls, the permeability and thickness of these water films decrease. In 1975 Loch and Miller reported that experiments had shown that ice in a frozen fringe beneath an ice lens could move (by regelation) at the same velocity as the lens in a process identified as secondary heaving. Raats (1975) developed a general set of transport equations for unsaturated, ice-free soil based on the concepts of irreversible thermodynamics. In 1978 Miller brought about the final development of a model of secondary frost heave. The criteria for the initiation of a new ice lens within the frozen fringe below a growing lens were better defined by equations for the conservation of mass and energy for a descending freezing front.

The 1980's witnessed much activity both in small scale frost heave modelling and large scale field experimentation. Much of the research activity was focused on proposals for large diameter buried chilled gas pipelines planned to transect continuous and discontinuous permafrost. Gilpin (1980), Konrad and Morgenstern (1980) and Takagi (1985) published their "new" frost heave models. While based on sound scientific data the models still had problems in predicting the influence of frost heaving. Forland and Ratkje (1980) renewed the belief that irreversible thermodynamics must be applied to the problem of predicting frost

heave of soils and rejected the use of the Clapeyron equation. In conjunction with the development of new frost heave models which were based once again on variations of the frost heave apparatus used by Taber, large scale frost heave model results were published by Nixon (1983) and Williams (1982, 1984, 1989). The Canada-France Pipeline Ground Freezing experiment in Caen, France, and the Calgary Ground Freezing Experiments allowed researchers to carry out full scale frost heave modelling of buried chilled pipelines transecting frost susceptible and non-frost susceptible soils.

Today, in the mid 1990's we still find ourselves with inadequate explanations for the mechanics of frost heaving, and no reliable test method for predicting frost heave susceptibility of soils. Many models purport to explain it, but they all suffer from the common fault of little or no experimental verification. An emphasis is now being placed on the experimental nature of research in frost heaving, while continuing to review and revise the various assumptions and approaches the models make.

1.3 Cryogenic alteration of soil structure

It is well known that freezing affects the arrangement of soil pores and particles, that is, the structure of the soil, and these effects persist to some degree after the soil is thawed. Kokkonen (1930) was the first to report

that soil fabric types were created by ice lensing, a phenomenon which was later partially expanded by Taber (1929). The growth of an ice lens combined with the consolidation resulting from the cryosuction in the unfrozen soil can create opposite effects. While on one hand soil pores are often widened and elongated by the growth of segregated ice lenses, on the other hand the soil is compressed / consolidated to form aggregates. Aggregates and elongated pores have been shown to persist after thaw because of the partial irreversibility of the consolidation process (Dumanski, 1964; Pissant, 1970; Van Vliet-Lane, 1985; White, 1991, 1992; White and Williams, 1993, 1994). The process of aggregation of fine sediment types is extremely important because of the modification these changes bring about to mechanical and hydraulic properties of soils, namely shear resistance and hydraulic conductivity.

Micromorphological analysis of soil microstructure created by cryogenic processes was not initiated until the early 1950's (Fitzpatrick, 1956) and has been extensively utilised in the field of Quaternary Geology during the last decade (Chartre, 1980; Harris, 1981, Van Vliet-Lane, 1982, 1987; and Tarnocai and Smith, 1989). Major reviews on cryogenic fabrics point to a growing interest in periglacial processes as recorded in the microstructure (Van Vliet-Lane, 1985; Harris, 1985; Yershov, 1987; White, 1992; Fox, 1994; White and Fox, 1995). Microstructures such as silt

capping, prismatic and platy microstructures, microinjections and microundulation have been well documented (Van Vliet-Lane, 1984, 1985, 1987) and attributed to cryogenic processes present during various periglacial periods throughout the Pleistocene.

The occurrence of repeated freeze-thaw cycles in fine-grained soils during the normal course of a Canadian winter has been extensively studied. It is widely acknowledged that freezing and thawing affects the arrangement of soil particles and pore spaces and thus their engineering properties (Yershov, 1987; Chamberlain, 1990; Konrad, 1989; White, 1992). The effects of freeze-thaw cycles on the frost susceptibility and microstructure of soils have, however, generally been ignored by engineers (Chamberlain, 1981). Experiments carried out in laboratories in Caen, France and Liege, Belgium illustrate that both platy and prismatic macrostructures as well as vesicles develop under appropriate thermal and hydraulic conditions (Van Vliet-Lane, 1984; White, 1991). Platy macrostructures were similarly observed to develop in saturated soils subjected to repeated cycles of freezing and thawing (Dumanski, 1964).

Chamberlain and Gow (1979) reported reduction in void ratios and large increases in vertical permeability. This rather incongruous behaviour was attributed by Chamberlain and Gow to the formation of polygonal shrinkage cracks for soils with high clay-size fractions, and by White and

Williams (1994) to the formation of an extensive network of planar voids for soils with predominately silt-size fraction. For clayey silts, no shrinkage cracks were observed and Chamberlain and Gow suggested that the increase in permeability is caused by a reduction in the volume of clay-containing aggregates that formed from repeated freeze-thaw cycling.

Subsequent freeze-thaw permeability tests performed by Chamberlain et al (1990) on four compacted, frost-susceptible soils also illustrated the extent to which vertical permeability was increased as a function of freeze-thaw cycling. Konrad (1989) reported similar findings on the effects of freeze-thaw cycles on the freezing characteristics of a clayey silt at various over-consolidation ratios. White's (1991, 1992) and White and Williams' (1993, 1994) studies on micromorphological changes in soil structure and pore-size distribution revealed how alternating freeze-thaw cycles resulted in the alteration of the fabric of a frost susceptible soil and its vulnerability to frost heave. The complex processes responsible for the cryogenic alteration of a soil's microstructure are not well understood or defined; this should therefore be taken into consideration when trying to assess geotechnical properties of soils. It may be suggested that by analysing and correlating cryogenic microstructure and physical properties a more thorough understanding of cryogenic alteration of frost heave charac-

teristics of fine-grained soils can be obtained. Therefore, the principal objective of the present study is to determine the interrelationship that exists between soil microstructure created by cryogenic processes and the corresponding changes in geotechnical properties of clay and silt soils.

1.4 Micromorphology of soils

In the microscopic fabric we are able to read the history of the soil as we may a book. We need only to learn to interpret that which we find in it (Kubiena, 1938).

The direction of micromorphology was established by this theme in Kubiena's book *Micropedology* (1938). In it Kubiena suggested the use of the microscope to study the morphology of soils as a basis for interpreting the processes involved in soil genesis. Kubiena's approach was further developed in the publication *Entwicklungslehre des Boden* (1948) in which he used micromorphological evidence to support a generic approach to soil development.

Micromorphological interpretation of soil genesis was thus born and has been based on many assumptions and hypotheses about soil behaviour and the processes responsible for the development and alteration of soil fabric. As Brewer (1973) summarised, "identification of microscopic features begins by accumulating data on the optical properties of the constituents that form the features". Interpretation of the

processes involved in the formation of soil features depends on hypotheses of soil-forming processes as well as some knowledge of both chemical and physical properties (Bullock, 1991).

Micromorphology, today, continues to contribute to the fundamental understanding of soil-forming processes and the microstructural features they produce. To date, most micromorphology research has been restricted to in-depth studies of soils which have not been subjected to alteration by cryogenic processes. The micromorphological study of soil microfabric created by cryogenic processes has, in the author's view, been under utilised. Although some research has been carried out by scientists such as Khonischev, Fedorova and Yershov in the Soviet Union, and Van Vliet-Lane in France, little literature has been translated and published in North American journals. Micromorphology combined with physical and chemical test methods of soil science and geotechnical engineering could help us to gain a better understanding of soil processes such as freeze-thaw which may affect their mechanical and thermodynamic properties and, it is hypothesised, the frost heave characteristics of soils.

A geotechnical engineer requires information that can be utilised in the assessment of a soil's behaviour; thin sections are often used to obtain information about the genesis of a soil (as in the case of a pedologist). This

poses a new challenge and perhaps utility for the science of micromorphology. Misinterpretation of a soil's genesis is generally of little or no consequence to a pedologist who arrives at the wrong conclusion, except for a certain amount of lost pride. The misinterpretation with regard to predicting the behaviour of soils for engineering purposes, however, could be quite catastrophic. Today, geotechnical engineers and soil scientists are in the process of accumulating data about the behaviour of soil fabric types and ultimately, may be able to make correlations between behaviour and fabric (Fitzpatrick, 1984; White, 1992). It is the intent of this present study to evaluate whether or not micromorphological and image analysis techniques can be utilised to evaluate alterations to rheological and geotechnical properties of fine-grained soils. Micromorphology and image analysis, when combined with geotechnical properties testing, could prove to be a practical technique for the assessment of a soil's behaviour under freezing conditions over the service life of much of Canada's infrastructure.

1.5 Objective of thesis research

In order to properly evaluate microstructural alterations that frost susceptible soils may undergo when exposed to cryogenic processes, a program consisting of small and large scale laboratory research was undertaken.

The specific objectives of this study were:

- 1) To determine the extent to which four frost-susceptible soils, prepared at two dry densities corresponding to the upper and lower end of their respective Proctor curves, may undergo micro structural alteration, that is, reorganisation of their fabric components and pore space distribution when exposed to freeze-thaw cycling;
- 2) To evaluate to what degree changes in soil microfabric are reflected by changes in geotechnical properties such as hydraulic conductivity, porosity and soil water desorption; and
- 3) To present a cryogenic soil fabric index based on the genesis of soil microfabric associated with cryogenic alteration and the corresponding changes in geotechnical properties.

Chapter Two of this thesis presents an overview of frost susceptibility and its relation to frost heave and consolidation. Factors affecting frost heave, the mechanics of frost heave and existing frost susceptibility tests are reviewed. Chapter 3 summarises cryogenic microfabrics (the arrangement of soil particles and pore size distribution), and their development by freeze-thaw cycling. Banded fabrics and related structures are also discussed. Chapter 4 details the results from a program of laboratory evaluations undertaken to determine soil characteristics (grain size, clay mineralogy) and changes in geotechnical properties such

as porosity and soil water retention. Observations of frost heave and consolidation for clay and silt soils that were subjected to freeze-thaw cycles are also presented. Chapter 5 presents cryogenic fabric observations taken from the clays and silts as well as cryogenic induced translocation of the soil fabric components skeleton and plasma.

Chapter 6 presents the alteration of the test soils' hydraulic characteristics, specifically, hydraulic conductivity and soil water desorption of clay and silts. Chapter 7 details the structural alteration that the test soils have undergone, specifically pore size distribution and porosity using computer image analysis.

Chapter 8 consists of summary and conclusions and introduces a new cryogenic soil fabric index which, it is envisaged, geotechnical engineers and soil scientists can use to better predict the behaviour of fine-grained soils when exposed to freeze-thaw cycling.

CHAPTER 2

Frost Heave Characteristics of Soils

2.1 General overview of frost susceptibility

Freeze-thaw cycling and cold temperatures bring about changes in physical properties of subgrade soils. Freezing and thawing of fine-grained soil has been frequently observed to change the engineering properties, especially shear resistance and hydraulic conductivity of these soils (Williams, 1957; Chamberlain and Gow, 1979; Mackay, 1983; Van Vliet-Lane, 1985; White, 1992). Abrupt changes in soil texture and heave susceptibility tend to more substantial heaving of one soil compared with another soil, and may produce sharp differential heave or displacement (White, 1992).

Freezing affects the arrangement of soil particles and pore size distribution and these freezing effects persist under certain drainage conditions to some degree, after thaw

consolidation has taken place (Van Vliet-Lanöe, 1985). When frozen, fine-grained soils such as clays and silts are generally very strong, at least at low temperatures ($<10^{\circ}\text{C}$). Freezing of soils such as marine clays has at times been used to temporarily stabilize soil during construction of retaining walls, foundations, and tunnels (Jordon et al., 1994; Suzuki and Sawada, 1994). The behaviour of frozen soil retains the complexities of its main structural components of ice and soil composed of both coarse grains and clay size particles (Figure 2.1) but, in addition, is subject to complications arising from the unfrozen water interface between the ice and soil particles (Williams, 1982). Freezing does more than bond soil particles and ice crystals together. Negative pore water pressures generated during freezing at temperatures just below 0°C are such that there is a continuing movement of water, ice and skeleton components of the soil. The dynamic nature of frozen ground expresses itself in both macro and micromorphological changes which take place as a function of freeze-thaw cycling. Changes in soil structure caused by freezing and thawing are related to one dominant process, namely the segregation of ice. The freezing of fine-grained soils when they are exposed to ample supplies of water from the unfrozen zone results in ice segregation, usually as layers or lenses, with subsequent frost heave.

Figure 2.1: Main structural components of frozen soil

from: E. Penner, 1959, p. 7.

2.2 Mechanics of frost heave

The classic works of Taber (1929) and Beskow (1935) on the nature of frost heave and specifically, the migration of water to ice lenses, was the first serious attempt to identify the mechanisms responsible for frost heave. Taber attributed the migration of water to "molecular cohesion" and identified factors such as soil particle size, availability of water, pore size and rate of cooling as being responsible for controlling ice segregation. Beskow related suction pressure to "capillary rise" and defined an inverse relationship between the height of capillary rise to grain size and depth of water table. He showed the amount of heave to be dependent upon ground conditions such as soil type, the weight of overburden, freezing temperatures and availability of water.

Over the last forty years since these works were published a number of frost heave models have been proposed (Everett, 1961; Harlan, 1973; Gilpin, 1980; Konrad and Mogenstern, 1980, 1981; Miller, 1978, 1980; Shen and Konrad, 1993; Fremond and Mikkola, 1991). These models are based upon the fundamental principles of thermodynamics combined to a limited degree with experimental observations. While these models have succeeded in obtaining a better understanding of the frost heave phenomenon they remained unreliable in predicting frost heave susceptibility. Over

the past two decades three fundamentally different explanations for frost heave and ice segregation have been incorporated into these different models. They are the capillary theory, secondary heaving theory and segregation freezing theory. The capillary theory and secondary heaving theory, until recently, appeared to work well together when the capillary rise theory was applied to granular soils and the secondary heaving theory was applied to fine-grained soils such as clayey silts. The third, namely segregation freezing theory has proven to be at odds with these first two theories. Although the theories disagree about the mechanism of frost heave, they are in general agreement on the factors affecting frost heave.

The classic capillary model introduced by Everett (1961) is the simplest of the three concepts. It showed that a direct relationship exists between heave pressure and suction pressure that develops during the formation of ice lenses as a function of the soil's porous matrix. Penner (1957) observed that the magnitude of the suction pressure was related to the geometry of the soil's porous matrix. Penner later concluded (1959) that suction pressures develop as a result of freezing point depression and that soils with smaller pore sizes develop higher moisture tensions.

Penner's research contributed to the capillary model introduced by Everett (1961) as well as to the work of Everett and Haynes (1965) who introduced the now familiar

equilibrium thermodynamic formula for ice growth in soils. The capillary model for ice segregation takes the form of Equation 1:

$$P_i = P_w + \frac{2\sigma_{i,w}}{r_{i,w}}$$

where P_i = steady state heaving pressure at base of ice lens

P_w = pore water pressure

$\sigma_{i,w}$ = surface tension at an ice/water interface

$r_{i,w}$ = radius of ice/water interface

This model can only be applied to soils characterised by a uniform granular matrix and therefore adsorption forces are negligible. For soils with a wide range of grain sizes the choice of an appropriate value of $r_{i,w}$ however becomes more difficult. Penner (1973) reported that heaving pressures calculated from Equation 1 were too large when an average value of $r_{i,w}$ was used, but found better agreement when $r_{i,w}$ values of the smallest radius of pore openings were used. Maximum heave pressure therefore could be calculated if the $r_{i,w}$ values from the smallest radius of the pore openings through which the ice must penetrate as it grows was used.

Miller's (1972) disagreement with Everett's simple concept led to the introduction of a second concept to help explain the mechanism of frost heave, secondary heave.

Miller had concluded from the capillary model that the only kind of ice segregation that could occur would be in the formation of ice needles. Miller's model suggested that ice lenses penetrated into some of the pores formed by stationary soil particles below the ice lens itself. The region where the ice front propagates beyond these ice lenses Miller referred to as the "frozen fringe" (Figure 2.2) where both ice and water coexisted and transfer between the two phases occurred.

Phukan and Morganstern (1979) reported that the thickness of the frozen fringe ranged from less than one millimetre to several centimetres, depending on the soil type, pore sizes, temperature gradient and applied pressure, and suggested that these factors controlled the rate at which moisture migration occurs within the frozen fringe.

From the "capillary" and the "secondary heave" models we can now surmise that in slowly freezing fine-grained soil, ice lenses are initiated in a wide range of pore sizes at a temperature slightly below 0°C behind the freezing front (Williams and Wood, 1985). As the temperature decreases the chemical potential is gradually lowered and pore water freezes in progressively smaller pores. Water can exist in soil water systems in equilibrium with ice at temperatures considerably below 0°C . This water exists in small capillaries and as films adsorbed on the surface of soil particles (Burt and Williams, 1976).

Figure 2.2: The frozen fringe

modified from: K. O'Neill and R.D. Miller, 1985, p. 286.

Ice lens formation and spacing is controlled by the thermal and hydraulic balance at the freezing front; that is, where ice is formed. As long as the pore water pressure in the yet unfrozen soil remains higher than the pore pressure at the ice - water interface the ice lenses will form in a series, one below the other, thus reflecting changes of the thermal - hydraulic balance at the freezing front. Miller (1977) illustrated (Figure 2.3) how the changes of the thermal - hydraulic balance at the freezing front were related to varying pore ice pressure and pore water pressure within the frozen fringe during ice lens growth. Profile A illustrates the conditions prior to the initiation of a new ice lens; Profile B, immediately after initiation of a new lens; and Profile C shows conditions prior to initiation of yet another ice lens.

The ice and pore water pressures resulting from this process can be determined from the following form of the Clausius - Clapeyron equation, Equation 2 (Williams, 1982):

$$T - T_0 = \frac{(P_w - V_w - P_i V_i) T}{L}$$

where T is the segregation freezing temperature, T_0 is the normal freezing point, L is the latent heat of fusion, V is specific volume, P is pressure, and the subscripts w and i represent water and ice phases respectively. The relevance

Figure 2.3: Profiles of pore water pressure at the freezing front

p_u = pore water pressure
 p_i = pore ice pressure
 σ_n = neutral stress
 $\bar{\sigma}$ = effective stress

from: R.D. Miller, 1977, p. 70.

of this equation has been confirmed by experimental studies performed by Williams (1967). After the ice nucleates and begins to grow, a negative pressure gradient develops, and water begins to flow toward the growing ice lenses.

Suction forces (tensile stress) cause an increase in the effective intergranular stress and a lowering of the soil's moisture content in the immediate vicinity below the ice lens. There is a corresponding decrease in the void ratio of the soil (Yershov, 1990) which becomes compressed, and desiccated (Figure 2.4) with the development shrinkage cracks in this region. The initial lens therefore cannot grow beyond a certain point because of the desiccation of the underlying unfrozen soil.

Once the capillary feed is blocked, ice lenses can continue to grow by the slow migration of still unfrozen adsorbed water (Burt and Williams, 1976) along the surface of mineral grains. Using X-ray photography Penner and Goodrich (1980) were able to document the continued growth of ice lenses within the frozen soil. Observations reported by Smith and Williams (1990) suggest that a considerable thickness of soil can be affected by moisture migration and temperature gradient and the accumulation of ice with the resulting secondary frost heave then taking place.

Figure 2.4: Consolidation and desiccation of unfrozen soil
beneath ice lenses

2.3 Factors affecting frost heave

Experience in regions of seasonal ground freezing has shown that the amount of frost heave tends to be greatest in silt soils, and is almost absent in exclusively coarse grained materials such as coarse sand and gravel (Williams and Smith, 1989). Studies over the last four decades has demonstrated that the most important factors affecting frost heave are:

- soil texture;
- pore size composition;
- rate of heat extraction;
- temperature gradient;
- moisture conditions;
- overburden pressure (stress); and
- finally and most importantly from the research presented in this thesis, the combined effects of freeze-thaw cycling on soil microstructure.

Taber (1929) recognised that soils with no particles smaller than 74 μm simply did not heave. Casagrande (1931) suggested that soil grain size, the most easily measured soil property, should be used to define the limits of frost-susceptible soils. Lambe (1953), and Lambe et al. (1969) reported that the mineral types, particularly clay mineralogy have a pronounced effect on frost-susceptibility as the nature of the exchangeable ion can either enhance or inhibit

frost heave. Concentrations of only 0.1 to 1.0% of the clay mineral montmorillonite in silt soil cause an increase in frost heave. On the other hand, higher concentrations >1.0% of the same clay mineral caused a decreased frost heave (Chamberlain, 1981). Penner concluded in 1976 that soil texture, a measure of particle size gradation, is the most important physical characteristic of soil for the purpose of assessing its susceptibility to frost heave. His research determined that grain size, particle size gradation and mineralogy in turn are responsible for influencing the pore size distribution, pore water tension characteristics, frost heave pressures and the hydraulic conductivity of soil.

The influence of pore size distribution on frost heave was first pointed out by Taber in 1929. Penner (1957, 1959) and Williams (1963) illustrated how pore size was important in interpreting pore water tensions during the freezing process. Csathy and Townsend (1962) reported that "every essential factor in the mechanism of frost action is ultimately related to pore size". Hoekstra (1969) also showed that a good correlation existed between pore size and frost heaving pressure which ultimately affects frost heave.

The rate of heat extraction was first identified by Penner (1960) as a significant factor in the frost heave process. Kaplan (1970) concluded that the heaving rate is directly proportional to the heat extraction rate while Loch (1979) found that the rate of heave did not depend on the

rate of heat extraction (Chamberlain, 1981). This apparent contradiction was later explained by Penner (1972) and Hill and Morgenstern (1977) when they revealed that there is a limiting rate of heat extraction below which the rate of heave increases and above which the rate of heave decreases.

The temperature gradient was shown by Phukan and Morgenstern (1979) to affect the thickness of the frozen fringe and the hydraulic conductivity within the fringe. Gorlé's (1980) research illustrated that frost heave is strongly dependant on the temperature gradient and freezing rate (Figure 2.5). As soil water freezes latent heat is released upon phase change (water to ice). The rate of soil moisture migration to the freezing front affects the rate at which the 0°C isotherm will penetrate into the unfrozen soil. High temperature gradients may result in a fast penetration of the 0°C isotherm which in turn limits the time available for moisture migration. In contrast, a low temperature gradient will produce a slow frost penetration rate that will generally favour the migration of soil moisture to the freezing front where phase change takes place.

Free access to soil moisture (open system) is the basic prerequisite for the ice segregation processes in which there is a continuous growth of ice lenses. The greater and steadier the water supply is the greater is the amount of segregated ice that can form and accumulate (Van Vliet-Lanöe and Dupas, 1991). A typical moisture tension curve for

Figure 2.5: Effect of freezing rate on frost heave

from: D. Gorlé, 1980, pp. 779.

soils of various textures (Figure 2.6) illustrates how at saturation, moisture tension is zero, and as the moisture content decreases tension increases at a rate which depends on soil texture. For frost heave to occur the tension generated in the zone of freezing must exceed the tension in the unfrozen soil (Miller, 1977). As moisture tension increases the hydraulic conductivity decreases (Ingersoll and Berg, 1981) which results in a reduction in the rate of frost heave. The depth to the water table determines the moisture tension condition within the different horizons of a soil profile above the water table and has a major influence on both the rate of frost heave and its magnitude (Gorlé, 1980).

Taber (1929) and Beskow (1935) both reported that the application of an overburden pressure (applied stress) on a column of freezing soil resulted in decreases to the rate of frost heave. Penner and Ueda (1978) reported that the application of progressively increased amounts of applied stress resulted in a corresponding reduction of total heave for various soil types (Figure 2.7).

Several freeze-thaw cycles occur in the upper 10 to 20 cm of soils during the fall and spring in a normal Canadian winter. The effects of freeze-thaw cycling on the frost heave susceptibility of soils has however been generally overlooked or ignored by engineers. Jessberger and Carbee

Figure 2.6: Moisture tension curves for soils of different textures

from: P.J. Williams and M.W. Smith, 1989, p 184.

Figure 2.7: Reduction in frost heave rate with applied pressure

from: E. Penner and T. Ueda, 1978, p. 723.

(1970) were the first researchers to demonstrate experimentally the significance of this phenomenon by illustrating the effect of freeze-thaw cycling on thaw - CBR values for clay soils (Figure 2.8). Chamberlain and Gow (1978) reported that freezing and thawing of silt and clay slurries resulted in increases to bulk density, hydraulic conductivity and reductions in void ratios (Figure 2.9). This incongruous behaviour was attributed to the rearrangement of soil skeleton grains and in the case of the clay soil, to the development of desiccation cracks beneath the freezing front.

Konrad (1989) reported similar findings on the effects of freeze-thaw cycles on the freezing characteristics of a clayey silt at various over-consolidation ratios. White (1991, 1992) and White and Williams' (1993, 1994) studies on micromorphological changes in soil structure and pore size distribution revealed how freeze-thaw cycles resulted in the alteration of the fabric for four frost susceptible soils prepared at different dry densities. Studies to date have revealed that changes in microstructure are responsible for increasing or decreasing a soil's permeability and this in turn affects the soil's frost heave characteristics. The complex nature of the various cryogenic processes responsible for this behaviour is as yet not well understood. It is anticipated that the research undertaken in this thesis

Figure 2.8: Effect of freeze-thaw cycling on thaw-CBR values

Freeze-thaw cycling causes progressively smaller thaw-CBR values, particularly for clay soils

from: H.L. Jessberger and D.L. Carbee, 1970, p. 18.

will reveal the complex interrelationships that exist between cryogenic processes and the development of new microstructural fabric types as well as the implications that these changes have on geotechnical properties of fine-grained soils.

2.4 Frost-susceptibility tests

Over the last sixty years five fundamentally different approaches to assessing the frost susceptibility of soils have been developed. A survey carried out by Chamberlain (1982) discovered in excess of one hundred methods of frost susceptibility determinations based on one or a combination of these approaches. The methods identified are based on particle size characteristics, pore size characteristics, soil water testing, soil / water / ice testing and finally, frost heave testing. The reliability of these methods is largely dependant upon the degree to which the factors affecting frost heave are taken into consideration.

The selection of the appropriate approach to determine the frost susceptibility of a given soil is usually based on expediency on the part of the engineer. Engineers as well as soil scientists are often under pressure to produce sound, reliable data at a finite cost within a usually limited time frame.

The simplest approach, namely, particle size determination has proven to be the most popular test method because

it is fast and requires little additional testing. In its most basic form particle size tests include only grain size determinations. Sixty-four years after Casagrande (1931) introduced his criteria for determining frost susceptibility, this criteria is still widely used. The particle size test method (grain size) requires the determination of the percentage of grains finer than 0.92mm and a uniformity coefficient ($C_u = D_{60}/D_{10}$, where D_{60} and D_{10} equal the particle diameters corresponding to 60% and 10% finer on the grain size distribution curve respectively). A more rigorous particle size classification system was introduced by the U.S. Army Corp of Engineers in 1965; it required more information about the entire grain size curve and the Atterberg limits. Armstrong and Csathy (1963) introduced the concepts of zones of frost susceptibility to the standard grain size curve (Figure 2.10), an approach which was subsequently adopted by the Canadian Department of Transportation. Townsend and Csathy's (1963) study of the field performance of frost susceptible soils illustrated how these zones of susceptibility resulted in the rejection of some frost susceptible soils along with the rejection of non-frost susceptible soils from time to time. A review of the reliability of all the grain size methods in determining frost susceptibility (FS) (Chamberlain, 1982) revealed that the overall reliability of these test methods varied between 0.38 to 0.91 (Table 2.1).

Figure 2.10: Zones of frost susceptibility on the standard grain size curve

from: M.D. Armstrong and T.I. Csathy, 1963, p. 184.

Table 2.1: Performance of grain size frost susceptibility criteria

User of test*	Reliability in predicting		No. of borderline soils	Overall reliability	User of test*	Reliability in predicting		No. of borderline soils	Overall reliability
	Non-frost- susceptible soils	Frost- susceptible soils				Non-frost- susceptible soils	Frost- susceptible soils		
Alberta	0.80	0.36	0		Nebraska	0.80	0.56	2	0.64
Arizona	0.80	0.45	0	0.56	Netherlands	0.80	0.73	0	0.75
Asphalt Institute	0.80	0.82	0	0.81	New Brunswick	0.80	0.64	0	0.69
Beskow	0.80	0.55	0	0.63	Newfoundland	0.60	0.82	0	0.75
Bonnard & Recordon	0.80	0.73	0	0.67	New Hampshire	0.80	0.45	0	0.56
Bonnard & Recordon	0.60	0.73	0	0.69	New York	0.80	0.36	0	0.50
Brudal	0.60	0.45	0	0.50	Nielson & Rauschenberger	1.00	0.36	0	0.56
Can. Dept. Trans.	0.60	0.82	0	0.75	Norway	0.80	0.36	0	0.50
Carothers	0.80	0.55	0	0.63	Nova Scotia	0.80	0.55	0	0.63
Casagrande	0.80	0.73	0	0.75	Ohio	0.80	0.36	0	0.50
Colorado	0.67	0.75	5	0.73	Ontario	1.00	0.27	0	0.50
Connecticut	0.80	0.55	0	0.63	Ontario	1.00	0.64	0	0.75
Croney	1.00	0.36	0	0.55	Orama	0.40	0.82	0	0.69
Delaware	1.00	0.27	0	0.50	Oregon	0.80	0.55	0	0.63
Denmark	0.80	0.55	0	0.63	Oregon	0.80	0.18	0	0.38
Ducker	0.80	0.73	0	0.75	Pietrzyk	0.80	0.40	1	0.53
Floss	0.80	0.55	0	0.63	Quebec	0.60	0.73	0	0.69
Idaho	0.40	0.82	0	0.69	Riis	0.80	0.73	0	0.75
Illinois	1.00	0.18	0	0.44	Ruckli	0.80	0.36	0	0.50
Iowa	0.80	0.45	0	0.56	Saskatchewan	0.80	0.55	0	0.63
Japan	0.60	0.82	0	0.75	Schaible	1.00	0.36	0	0.56
Jessberger & Hartel	0.60	0.64	0	0.63	Switzerland	0.67	1.00	5	0.91
Jessberger	0.80	0.64	0	0.69	Turner & Jumikis	1.00	0.27	0	0.44
Kansas	0.80	0.36	0	0.50	U.S. CAA	0.80	0.55	0	0.56
Linell & Kaplar	0.80	0.82	0	0.81	USAE WES	0.67	0.71	6	0.70
Maag	1.00	0.30	2	0.50	U.S. Army Corps of Engrs.	0.67	1.00	5	0.91
Maine	0.40	0.82	0	0.69	Vermont	0.80	0.73	0	0.67
Maryland	0.80	0.45	0	0.56	Vlad	0.80	0.50	0	0.56
Massachusetts	0.80	0.55	0	0.63	Washington	0.80	0.64	0	0.69
Mass. Tnpk. Auth.	0.80	0.55	0	0.63	West Germany	0.60	0.82	0	0.75
Minnesota	0.80	0.55	0	0.63	Wisconsin	0.40	0.82	0	0.69
Morton	0.80	0.45	0	0.56	Wyoming	1.00	0.36	0	0.73

*A description and reference for these tests are given in the text. Many of the tests reviewed in the text are not included in this analysis because they required more information than was available.

from: E.J. Chamberlain, 1982, p. 71.

The relationship between pore size and a soil's frost-heave susceptibility was first identified by Taber in 1929. Penner (1959) also reported the importance of pore size and its influence on the frost susceptibility of soil. Townsend and Csathy (1963) were the first to suggest using pore size as an index of FS. Using the capillary rise method (employed to determine pore size distribution or P_u) they established that when $P_u > 6$ (where $P_u = P_{90}/P_{70}$) based on pore size distribution curve between 90% (P_{90}) and 70% (P_{70}), limits become steeper with increasing frost susceptibility. Gaskin and Raymond (1973) suggested that the capillary rise method was a good indicator of true pore size distribution and had the best correlation with distribution. Reed et al (1979) indicates that the principal advantage of using the pore size distribution criteria was that consideration was given to the moisture and density variables which in turn affect compaction. The principal disadvantage of the Csathy and Townsend capillary rise test is that it takes up to thirty-five days to generate the water desorption data required to produce the pore-size distribution curves.

Soil water interaction tests include moisture tension tests, capillary rise tests and saturated and unsaturated hydraulic conductivity tests. These test methods rely on the interaction of soil and water, and because they address both variables they are one step closer to properly assessing the frost heave susceptibility of soils.

Williams (1966) demonstrated that an air intrusion value established from the moisture-tension tests could be utilised as an indicator of a soil's susceptibility to frost heave. Wissa et al (1972) proposed that a better way to determine a soil's susceptibility to frost heave could be achieved from the product of an air entry value and the unsaturated hydraulic conductivity. Chamberlain (1982) reported that considerable frost heave and moisture movement could occur at tensions well above the air intrusion values thus discounting the use of this method.

Soil / water / ice interaction tests which involve the freezing and subsequent thawing of a soil are used to measure frost heave stress and pore water suction.

Penner (1959) reported that frost heaving pressure is a function of dry densities for a single material. Hoekstra et al. (1965) observed that the maximum pressure during a restrained freezing test could be used as a characteristic value for a given soil type. Later Hoekstra and Chamberlain (1965) suggested that frost heave criteria could be based on the maximum heave pressure (Figure 2.11) which develops at a stationary freezing front where steady state heat flow conditions prevail. Wissa and Martin (1968) recommended a procedure for conducting frost heave stress tests and how to use the heave stress data to predict frost susceptibility. They inferred that the slope R of the straight line portion of a curve generated by the plotting of the logarithm of

Figure 2.11: Frost susceptibility classification based on maximum frost heave pressure

from: E.J. Chamberlain, 1982, p. 48.

the frost heave stress as a function of time (Figure 2.12) could be interpreted as being characteristic of frost susceptibility.

The most direct method of assessing frost susceptibility is by subjecting a given soil specimen to a freeze-thaw cycle in a frost heave test apparatus. Chamberlain's (1982) review of frost heave tests revealed a wide range of methods for determining the frost susceptibility of soils and concluded that no one test gave desirable results for all soil types over the full range of moisture and temperature conditions that might prevail in-situ. Most of the direct frost heave tests used the amount of frost heave at a given time or the ratio of frost heave as the critical factor in determining the frost susceptibility of soils. Penner and Ueda (1978) concluded that the heat extraction rate and not the frost penetration rate is the fundamental parameter in the freezing process and that the ratio of heat extraction used in the direct laboratory frost heave test could be related to field data. Subsequent research (Morgenstern and Konrad, 1980, 1981; Fremond and Blanchad, 1983) revealed that the frost heave rate was related to the temperature gradient maintained in the frozen fringe.

Figure 2.12: Frost heave stress as a function of freezing time

from: A.E.Z. Wissa and R.T. Martin, 1968, p. 71.

CHAPTER 3

Cryogenic Microfabrics

3.1 General

Cryogenic microfabrics form as a result of cryogenic alteration and are defined by their morphological expression or by the cryogenic processes (compressional, shear and tensile stresses) responsible for their formation.

Cryogenic alteration includes particle sorting, accumulation of fines on the surface of skeleton grains, vertical alignment of skeleton grains, ice lens formation and the displacement of soil material by cryosuction. In the freezing soil, formation of ice results in the water being confined progressively in smaller spaces. The free energy of the water falls on this account. This effect can be referred to as the suction, or cryosuction generated by soil freezing and it is the cause of migration of water to the freezing zone (Williams and Smith, 1989). Micromorphological inter-

pretation of soil genesis has, historically, been based on many assumptions and hypotheses about soil behaviour and the processes responsible for soil development. These processes involved in the creation of soil features is a function of soil-forming processes as well as the chemical and physical properties of a soil. Today, micromorphology contributes to the fundamental understanding of soil forming processes. Although some research has been carried out to try and relate cryogenic alteration to the development of specific types of microstructures (Van Vliet-Lanöe, 1985) little literature exists on the implications these changes have on the geotechnical properties of clay and silt soils. Subsequently, the consequences for sound engineering design when dealing with the behaviour of fine-grained soils in cold climates has not been well researched.

This chapter provides a review of research carried out to date on microstructural fabrics which develop when internal movement and reorganisation of soil fabric components and alteration of pore-size distribution occurs. The specific objectives were:

- 1) To determine the extent to which research has been carried out on the cryogenic alteration of fine-grained soils; and
- 2) To establish what cryogenic processes are responsible for the formation of distinctive microfabrics, specifi-

cally those created by freeze-thaw cycling and segregated ice lensing.

3.2 Cryogenic alteration of clay and silt microstructure

Kokkonen (1930) reported that ice lensing in fine-grained sediments was responsible for imposing macro and micro structure in fine-grained sediments. This micro structure or aggregation of sediment imposed by ice lensing has also been studied after thawing (Oumanski, 1964, Pis-sant, 1970, Van Vliet-Lanöe, 1985.)

Until the late 1980's the effects of freeze-thaw cycling on the geotechnical properties of soils had not been widely studied. Freeze-thaw permeability test results performed by Chamberlain (1990) on four compacted frost susceptible soils illustrated that vertical permeability stabilised after eight freeze-thaw cycles thus inferring that no further changes to soil microstructure took place (Figure 3.1). Konrad (1989) reported similar results after carrying out a number of freeze-thaw cycles on clayey silt samples prepared at various overconsolidation ratios. Microfabric studies were carried out by White (1991) as well as by Van Vliet-Lanöe and Dupas (1991) on soil samples taken from the Canada-France Pipeline Ground Freezing Experiment located at the Station de Gel, Caen, France which is described in detail in Chapter 4. These studies revealed that cryogenic fabric types, pore size distribution, poros-

Figure 3.1: Effect of fourteen freeze-thaw cycles on the permeability of four compact clays

Vertical permeability stabilises after eight freeze-thaw cycles

from: Chamberlain et al, 1990, p. 100.

ity and hydraulic conductivity of a frost susceptible silt had been altered after exposure to only four freeze-thaw cycles. Table 3.1 indicates how, in successive freeze-thaw cycles of the Caen experiment, the frost heave susceptibility of the silt continued to increase. The increasing frost heave experienced by the silt was brought about by the reported intense segregated ice lensing (Smith and Williams, 1990).

The reported increases in hydraulic conductivity and changes to pore size distribution (White and Williams, 1993) can be attributed to intense ice lensing having developed as a result of high soil moisture suction in the freezing zones. These cause an increase in the effective stress in the region below the freezing front during the formation of segregated ice lensing. Othman and Benson (1993) illustrated how hydraulic conductivity of compacted clay soil increased as a function of the number of freeze-thaw cycles and how the number of ice lenses forming in the soil increased from one freeze-thaw cycle to the next. Concurrent with these processes, soil skeleton grains and plasmas (clay size particles), through processes of aggregation and compression are consolidated between ice lenses which create new pore spaces. Observations presented in this thesis would suggest that unless hydraulic or thermal conditions are modified (via a high water table) newly created

Table 3.1:

Heave of buried chilled pipe in Caen silt (day 100)

Freeze Cycle	Heave (cm)	% Increase
Second	9.88	--
Third	10.77	9
Fourth	11.40	5.8

cryogenic fabrics remain stable and structural changes are thus irreversible.

Stability of the resulting cryogenic fabrics created by segregated ice lensing have also been studied after thaw consolidation processes have taken place (Dumanski, 1964; Pissant, 1970; Van Vliet-Lane, 1985; White, 1991, 1992; White and Williams, 1993, 1994). The aggregation of fine-grained sediments is extremely important because it modifies irreversibly the hydraulic conductivity (White, 1991) and also the mechanical properties of the material such as frost susceptibility (White, 1992), shear resistance, and lensing capability (Van Vliet-Lane and Dupas, 1991).

Segregated ice lensing is responsible for increasing both the soil's horizontal and vertical permeability in the near surface layer, permeability which remains intact or possibly enhanced by each subsequent cycle. The significance of thermal gradient on the development of soil morphology and in turn, its permeability, was demonstrated in the Canada-France ground freezing experiment (White, 1992). In zones of the experiments where a low temperature gradient ($0.05^{\circ}\text{C}/\text{cm}$) existed a fragmoidic fabric was observed to have developed (Plate 3.1). This cryogenic fabric designates morphology having planar pores (0.1 to 1.0 mm in width) separating highly compacted, often elongated soil units; such fabric was interpreted by Van Vliet-Lane (1985) to result from ice lens formation, and shown by Pawluk (1988)

Plate 3.1:

Fragmoidic fabric with temperature gradient of $0.05^{\circ}\text{C}/\text{cm}$

Planar pores (a) left behind after ice lenses have melted

Frame is 13.5 mm in width

and White and Williams (1994) to form from repeated freeze-thaw cycles. The fragmoidic fabric was observed to change to a fragmic fabric (Plate 3.2) as a function of changes to firstly the thermal gradient ($0.025^{\circ}\text{C}/\text{cm}$), depth below the pipe, distance away from the buried chilled pipeline and secondly, number of freeze-thaw cycles (Figure 3.2). The fragmic fabric designates morphology having compact aggregates separated by planar pores (0.1 to 0.25 mm in width). White and Williams (1994) observed that cryogenic fabric types can remain intact from one cycle of freeze-thaw to the next and indeed were enhanced up to and including five cycles of alternating freeze-thaw. It was hypothesised that the growth and corresponding expansion of segregated ice lenses result in the elongation and widening of existing pore spaces in soils and the creation of new pore spaces for freeze-thaw cycles two through five.

The position of segregated ice lenses in the silt profile relative to both the ground surface and at distance from the buried chilled pipe is shown in Plate 3.3. Ice lens spacing was observed by the author at the end of the fourth freeze cycle to vary from closely spaced ice lenses (5 mm to 10 mm apart) in the upper soil layer, to ice lenses spaced 20 mm to 30 mm apart at greater depths and at distances from the pipeline. The spatial distribution of planar pores after thaw consolidation was similar to the

Plate 3.2:

Fragmic fabric with temperature gradient of $0.025^{\circ}\text{C}/\text{cm}$

Planar pore (a) left behind after ice lenses have melted

Frame is 13.5 mm in width

Figure 3.2: Thermal regime of the Caen silt adjacent to the buried chilled pipe at end of fourth cycle of the SS ground freezing experiment

Plate 3.3: Spatial distribution of segregated ice lenses
in Caen silt sample trench next to buried chilled pipe, B-B
axis

Ice lenses are black lines in trench wall

distribution of ice lenses which created them during freezing. Planar pores were observed in the fragmoidic fabric to be closely spaced (1.0 mm to 2.0 mm, Plate 3.1), while at depth planar pore spacing was observed to become more irregular and ranged from 2.0 to 5.0 mm apart in soil samples dominated by fragmic fabrics.

The development of this pattern of spacing is indicative of a slow freezing soil characterised by a predominately silty texture whose capillary fringe is within reach of the water table. Under steady water supply conditions such as those maintained in the Canada-France Pipeline Ground Freezing Experiment where the flow of heat exceeds the rate of latent heat release, ice lenses develop, forming in a series one after the other.

The observed spacing between ice lenses and their products, planar pores, reflect the changes in thermal and hydraulic balance at the freezing front, that is, where ice formed. Spacing was observed to increase as the rate of cooling decreased as a function of depth from the surface and distance from the buried chilled pipeline.

3.3 Development of cryogenic microfabrics

Cryogenic microfabrics are defined as "the distinct micromorphology resulting from the effects of freezing and thawing processes" (Harris and Cook, 1988). Over the last three decades research has been conducted in both small

scale laboratory experiments in which soil cores are subjected to numerous freeze-thaw cycles, and large scale ground freezing experiments such as those conducted at the Station de Gel. These studies have yielded insight into the interrelationships which exist between cryogenic processes and the formation of specific fabric types (White, 1991). These observations have been complemented by field micromorphological observations of cryogenic microfabrics in modern and fossil periglacial environments and their related environmental conditions including drainage and sediment types (Fitzpatrick, 1956, 1971, 1984; Harris, 1981; Fox, 1979, 1981; Tarnocai and Smith, 1989, 1991; Fedova and Yarilova, 1972; Van Vliet-Lane, 1982, 1984, 1985; White and Fox, 1995).

At the same time, over the past three decades scientists also have tried to establish what effect freeze-thaw cycling has had on soil microstructure and identify the controlling factors responsible for these changes.

Cort (1966) reported on experiments which involved cycles of freezing the soil from the surface down, or from the bottom up, and then thawing from the surface down. He inferred from grain size analysis of the soil samples that during the freezing process there is a tendency for coarse particles (<0.074 mm) to migrate to the freezing plane. Cort distinguished different types of frost sorting, that is, processes by which migrating particles were sorted into

uniform particle size. Vertical sorting occurred when freezing and thawing took place from the surface down, causing the larger particles to move upward in relation to the smaller particles. Lateral sorting also occurred when freezing and thawing were applied from the sides; the fine particles moved away from the freezing front leaving the larger particles near the cold side. Washburn (1973), French (1976) and White (1992) also observed the upward and downward movement of skeleton grains and clay sized particles which resulted from freezing and thawing.

Van Vliet-Lanöe's (1985) review of frost effects on soils summarised the major influences on soil structure in cold environments including ice lensing, frost heaving, soil solute concentrations, degree of cryodesiccation and periglacial movements. Pawluk (1988) subjected core specimens of clay loam to one hundred cycles of freeze-thaw from the surface downward. Throughout these freeze-thaw cycles moisture conditions within the test specimens were maintained between field capacity and saturation. This ensured that the soil had a high plasticity and that expanding ice lenses were unconfined. Granic and fragmic microfabrics were observed to develop near the surface of the specimens when the thermal gradient was high. Conversely, the central portion of the core specimens where the thermal gradient was lower was characterised by a platy microstructure. Pawluk also observed that soil pores created by ice lenses were

strongly oriented and elongated in a direction parallel to the freezing front reflecting the confining stress imposed by the overlying frozen soil. Coutard and Mucher (1984) observed an abundance of microstructures which included vesicles, platy structure and micro undulation created by ice segregation and thaw consolidation after applying twenty-five freeze-thaw cycles to a silt loam prepared in well defined layers.

As mentioned above, results from the Canada-France Pipeline Ground Freezing Experiment revealed that distinct gross morphologies had developed in the samples taken from the frozen annulus of soil surrounding the buried, chilled pipeline. White (1991, 1992), Van Vliet-Lane and Dupas (1992), and White and Williams (1993) noted that soil microstructure was altered directly in response to cryogenic and consolidation processes, but that the new cryogenic microstructures were stable and maintained their distinctive morphologies after thaw consolidation and may have been enhanced during subsequent freeze-thaw cycles. White and Williams (1994) showed that similar types of microfabrics develop in a wide range of frost susceptible soils which had undergone only ten freeze-thaw cycles.

The dominant morphologies (Figure 3.3) which developed in the zones around and immediately adjacent to the buried chilled pipeline are fragmoidic (Plate 3.1), fragmic (Plate

Figure 3.3: Spatial distribution of cryogenic fabrics in Caen silt adjacent to a buried chilled pipe, B-B axis

- PORPHYROSKELIC FABRIC
- FRAGMOIDIC FABRIC
- FRAGMIC FABRIC
- GRANOIDIC-PORPHYROSKELIC FABRIC

3.2) and porphyroskelic fabrics (Plate 3.4). These fabrics developed from a granoidic-porphyroskelic fabric (Plate 3.5) which had been created through compaction. The fragmoidic and fragmic cryogenic fabric types have been interpreted by Van Vliet-Lane (1985) to result from ice lens formation, and shown by Pawluk (1988), White (1992) and White and Williams (1993, 1994) to develop progressively from freeze-thaw cycles one through five. In contrast, some zones within the frozen annulus surrounding the buried chilled pipe were characterised by a dense porphyroskelic fabric which exhibited few or no distinct planar pores. Zones characterised by porphyroskelic fabric form as a result of consolidation of the original granoidic porphyroskelic intergrade. From these observations there appears to be a correlation between cryosuction and zones characterised by dense porphyroskelic fabric observed between widely spaced planar pores.

3.4 Micromorphology of permafrost affected soil

Studies of seasonally frozen soils typical of southern Canada and of the seasonally frozen active layer in Arctic soils have shown that cryogenic processes are consistently a principal agent responsible for soil genesis. From early studies carried out by McMillan and Mitchell (1953), Duman-ski and Arnaud (1966) and Mermut and Arnaud (1981) it has been recognised that the most prominent microfabrics are

Plate 3.4: Porphyroskelic fabric with a temperature gradient of $0.15^{\circ}\text{C}/\text{cm}$

Dense ground mass, no distinct pore structure

0.5 m from side of pipe, 30 cm below surface

Frame is 13.5 mm in width

Plate 3.5: Granoidic-Porphyroskelic intergrade, unfrozen
Caen silt

Dense ground mass (porphyroskelic fabric) (a) separated by
zones of soil with irregular, weakly interconnected vugh-
shaped pores (granoidic fabric) (b)

1.0 m from side of pipe, 1.2 m below surface

Frame is 13.5 mm in width

characterised by microbanding. In contrast with the seasonally frozen soils of Southern Canada, Northern Canadian soils (Turbic Cryosols) are subjected to cryoturbation, a process which makes soil surfaces unstable and is responsible for internal displacement and mixing of soil horizons. Smith and Onysko (1990) attributed soil matrix deformation to ice pressure which induces creep when the soil matrix becomes stressed. Distinct patterns of morphology have been described by Fox and Protz (1981), Fox (1983), Tarnocai and Smith (1989, 1991), Smith et al. (1991) and Fox (1994). Turbic cryosols in arctic regions are characterised by internal reorganisation of both fine and coarse material with the alignment of uniform grain sizes often being reported (Fox and Protz, 1981). Soils in the northern extension of the Canadian high arctic archipelago are characterised by banded fabrics, silt cappings and platy microstructure in periglacial features such as earth hummocks (Brewer and Pawluk, 1975).

For the most part, cryogenic fabric types such as granic (Plate 3.6), granoidic (Plate 3.7), fragmic (Plate 3.2), fragmoidic (Plate 3.1) and microbanded fabrics (Plate 3.8) are influenced by two dominant cryogenic processes, namely, segregated ice lens formation and freeze-thaw cycling, in the active layer above the permafrost (White and Fox, 1995).

Plate 3.6: Granic fabric in Turbic Cryosol of earth hummock

Plate 3.7: Granoidic fabric in Turbic Cryosol of earth hummock

Frames are 8.5 mm in length
both from: C.A. Fox and R. Protz, 1981, p. 32.

Plate 3.8: Microbanded fabric in Caen silt used in SS and
UP ground freezing experiments

Accumulations of clay particles (a) separated by
coarse skeleton grains of silts (b)

Frame is 13.5 mm in width

According to Bunting (1983) banded microstructures in the high arctic regions are genetically related to a preferential mobilisation of fines to surmount banded sediments and accumulations of fines adjacent to melted lenses. Mermut and St. Arnaud (1981) introduced the term microband fabric for lenticular units (< 1 mm thick and 1 to 3 mm in length) composed of fine material. Microband fabrics are created by high freeze-thaw frequency, soil texture and degree of water saturation. Tarnocai (1994) illustrated how repeated freeze-thaw cycles at the surface occurring during the fall and spring were the driving force behind cryogenic processes producing Turbic Cryosols located in the Mackenzie Valley (Table 3.2). Freeze-thaw processes were observed to operate for approximately five to ten weeks per year in these soils. These freeze-thaw cycles have been produced by the movement of two freezing fronts, one moving downward from the soil surface and the other upward from the permafrost table.

Smith et al. (1991) reported that unvegetated surface horizons typical of nonsorted circles (mud hummocks) were granular and characterised by granic and granoidic cryogenic fabric types.

Tables 3.3 (earth hummocks) and 3.4 (non-sorted circles) (presented in detail by Tarnocai et al., 1993) illustrate how granic fabric is the main fabric type produced by freeze-thaw cycles in earth hummocks and how frag-

Table 3.2: Number of yearly freeze-thaw cycles in three
turbic cryosols (0 - 20 cm below surface)

**Table 1: Number of Yearly Freeze-Thaw Cycles
in Three Soils in the Mackenzie Valley**

Pedon No.	Location		Year		Number of Freeze- Thaw Cycles		
	Lat. (N)	Long. (W)	Fall	Spring	Fall	Spring	TOTAL
P-i	68° 58' 09"	133° 32' 54"	1991	1991	8	26	34
1-2	68° 06' 39"	133° 28' 29"	1989	1990	8	19	27
7B-1	68° 36' 34"	123° 37' 52"	1991	1991	16	22	38

from: C. Tarnocai, 1994, p. 147.

Table 3.3: Cryogenic fabric distribution in an earth
hummock

earth hummock; fine silty till; moderately well to poor internal drainage; 3% slope to SW					
Fabric	Horizon (Depth cm)				
	Oh (Oa) * 3-0	Bm (Bw1) 0-10	Bmy (Bw2) 10-35	BCy (BC) 35-65	Ahy (A) <5
Granic					
Ortho-	x	x		x	
Phyto-	x	x		x	
Humi-	x	x		x	
Mull-		x			
Matri-					x
Granoidic					
Phyto-					
Humi-					
Mull-	x			x	
Matri-					
Fragmic					
Matri-					
Fragmoidic					
Matri-					
Isoband					
Banded					
Conglomeratic					
Mull-					
Matri-					
Ortho-					
Orbiculic	x		x		x
Suscitic			x	x	x
Porphyroskeitic	x	x	x	x	
Porphyric					
Adporphyric					
Layered					
Agglomeroplastic					
* U.S.A. soil classification					

from: C. Tarnocai et al., 1993, p. 9.

Table 3.4: Cryogenic fabric distribution in a
non-sorted circle

nonsorted circles (mudboils); mixed Eolian and shale Saprolite; imperfectly drained; 2% slope				
Fabric	Horizon (Depth cm)			
	Bmy1 (Bw1)* 0-15	Bmy2 (Bw2) 0-30	Cy (C) 0-25	Bmy3 (Bw3) 5-15
Granic Ortho- Phyto- Humi- Mull- Matri-			x	x x
Granoidic Phyto- Humi- Mull- Matri-	x	x		
Fragmic Matri-	x	x	x	
Fragmoidic Matri-		x		
Isoband				
Banded				
Conglomeratic Mull- Matri- Ortho-			x	x
Orbiculic				
Suscitic				
Porphyroskelic	x	x		
Porphyric				
Adporphyric				
Layered				
Agglomeroplastic				
* U.S.A. soil classification				

from: C. Tarnocai et al., 1993, p. 9.

mic, fragmoidic and porphyroskelic fabrics are characteristic of fabrics which form in non-sorted circles (mud boils) as a result of intense segregated ice lensing. Similarities between these Turbic Cryosol fabric types and the processes responsible for their formation and cryogenic fabric types produced experimentally were described by White and Fox (1995). Soil fabric types in earth hummocks are created by freeze-thaw cycles in the upper horizon which produces a granular structure characterised by a granic fabric. At depth the lower horizons are characterised by sorted fabrics such as suscitic (Plate 3.9), orbiculic fabrics (Plate 3.10) and conglomeric (Plate 3.11). Typically organic matter occurs in the lower horizons (BCy) and as inclusion (Ahy) in the earth hummocks (Figure 3.4). Soil fabric types which characterise non-sorted circles (mud boils) are created primarily by segregated ice lens formation. Typically, granoidic, fragmic and fragmoidic fabric types are created by segregated ice throughout the upper horizons of mud boils (Figure 3.5).

3.5 Microbanded fabric and related structures

Advanced stages of cryogenic alteration are characterised by the microbanded (Mermut and St. Arnaud, 1981) or banded fabrics first identified by Kubiena (1938) and further described by McMillan and Mitchell (1953). Banded fabrics (Plate 3.8) are defined as "layers rich and

Plate 3.9: Susicitic fabric

Skeleton grains (b) shown in vertical or nearly vertical
(long axis) alignment and usually have an
accumulation of fine material (a) at the base

from: C.A. Fox and R. Protz, 1981, p. 31.

Plate 3.10: Orbiculic fabric

Skeleton grains (a) are arranged as regular circles or ellipsoids within a dense fine-grained plasma

from: C.A. Fox and R. Protz, 1981, p. 31.

Plate 3.11: Conglomeratic fabric

Rounded to elliptical F-members randomly set in a
ground mass of finer material (a)

from: C.A. Fox and R. Protz, 1981, p. 32.

Figure 3.4: Cross-section of turbic cryosol associated with an earth hummock

modified from: C. Tarnocai et al., 1993, p. 47.

Figure 3.5: Cross-section of turbid cryosol associated with non-sorted circles (mud boils)

modified from: C. Tarnocai et al., 1993, p. 79.

poor in plasma substances [that] follow one another in rhythmic succession in a more or less uniform skeleton pattern" (Kubiena, 1938). McMillan and Mitchell (1953) introduced the term "isoband fabric" when describing bands displaying uniformly distributed fine and coarse material. According to Dumanski and Arnaud (1966) the process of wetting and drying is just as important a process for the development of "isoband fabric" (platy microstructures) as is the freeze-thaw process.

Banded fabrics have been related to ice segregation, vertical translocation of fine material, in situ sorting and finally, to differential settling within a water saturated soil mass.

Fitzpatrick (1956) concluded from observations made of modern periglacial environments and from experiments that planar pores were formed by ice lenses; subsequent infilling of these pores with fine material by percolating water produced silt cappings. Fitzpatrick (1971) stated that "the upper part of the peds have a much finer texture due to the migration of fine particles mainly of silt size through the larger pore spaces left after the ice has thawed"; these peds actually resemble banded fabric. In seasonally frozen ground in Norway banded fabrics and silt capping are present in the subsurface of active solifluction lobes (Harris and Ellis, 1980); silt cappings were produced by vertical translocation of matrix material during the drainage of melt

water. The banded fabric was related by Harris and Ellis to the melting of ice lenses and subsequent accumulation of matrix material and the creation of lenticular aggregates by segregated ice layers.

While banded fabrics and related microfabrics have been widely reported and their cryogenic origins have been extensively discussed, additional cryogenic microfabrics associated with cryogenic processes have been identified more recently. These supplementary cryogenic microfabrics include undulating laminations and microinjections, fine fringement fabrics and granular microstructures.

Microundulations or wavy laminations were produced experimentally by Coutard and Mucher (1985) in a silt loam exposed to eighteen freeze-thaw cycles. Coutard and Mucher stated that frost creep processes are responsible for the development of microundulation and that mechanical stress resulted in shear planes which caused fragmentation of an argillaceous laminate and its vertical translocation. Van Vliet-Lane's (1985) field observation from Spitsbergen also associates the deformation of banded fabric to soil creep during the thaw consolidation phase.

Microinjections have been reported in both modern and fossil periglacial environments (Van Vliet-Lane, 1985). According to Harris and Cooke (1988) microinjection observed in non-sorted circles was induced by creep of over-saturated liquified sediments. Though microinjection can be produced

by cryogenic processes such as freeze-thaw, soft sediment intrusion may alternatively be produced during post-depositional pore water escape, producing water escape structures in sedimentary deposits. Washburn (1979) suggested that the development of differential cryostatic pressure was responsible for cryoturbation / microinjection of unfrozen sediments. When the two freezing fronts move towards each other in permafrost affected soils, unfrozen materials are trapped between them, generating cryostatic pressure. Since the freezing fronts are not uniform (some parts move faster than others) (Tarnocai, 1994) differential cryostatic pressure develops. In the fall unfrozen soil, typically contains a high water content and results in high plasticity and the soil being displaced from areas of high pressure to lower pressure.

The description of a fabric present in fine sediments by its orientation and distribution of birefringent fabric can be accomplished using crossed polarised light. Granostriated b-fabric, associated with alternating freeze-thaw cycles was explained by Fox (1983) who attributed this morphology to cryostatic pressure during the freeze-thaw cycles. Koniščev et al. (1975) explained a marked increase of oriented clay structures at the base of the active layer by a higher clay content and 'hydro-thermal' conditions, i.e., slow freezing and high moisture content. Van Vliet-Lanöe (1985) describes the formation of stress cutan on the

surface of cryogenic aggregates as a result of pressure exerted by growing ice lenses. B-fabrics may also be created by stresses associated with alternating wetting and drying (Brewer 1976) and therefore should be used with caution as a diagnostic feature since they also exist in non-periglacial environments.

3.6 Summary of cryogenic microfabrics

The major effects of cryogenic processes are expressed by changes in microstructure, the translocation of soil skeleton grains and clay size particles, aggregation, and the development of new pore space.

As stated earlier the formation of a granular macrostructure characterised by granic and granoidic fabric types is associated with repeated freeze-thaw cycles. Tarnocai et al. (1993) reported that earth hummocks were characterised by granular structures in the upper horizons produced by freeze-thaw cycles. Comparable granular macrostructures were also reported present in earth hummocks by Sanbon and Pawluk (1989). Granular microfabric should, however, be used with caution as a diagnostic feature associated with its periglacial environment. Granular microstructures may also be formed by biological activity, wetting and drying, and the precipitation of sesquioxide (Fitzpatrick, 1984).

Displacement of soil materials as a result of cryogenic processes leads to micromorphologic arrangements (cryogenic fabrics). Displacements include the alignment of the coarse particles as well as clay sized material (plasma) in the formation and internal rotation of aggregates, alignment of mineral particles, sorting of both coarse and fine fractions, and the protrusion / injection of soil material from one location in the soil profile to another. Compaction of the soil as a result of cryogenic processes include a consolidation of soil microstructure via cryosuction, below the warmest ice lens in unfrozen soil and between lenses. Pore space development is directly attributable to segregated ice lens development and growth which results in planar pores and desiccation cracks.

The effects of cryogenic processes in the development of specific cryogenic fabric types (Fox, 1993) is summarised in Figure 3.6.

Figure 3.6: Conceptual framework for characterising cryogenic processes and development of cryogenic fabric types

from: C.A. Fox, 1994, p. 5.

CHAPTER 4

Experimental Investigations

4.1 General

Experiments have been made to evaluate the cryogenic alteration of clay and silt soils exposed to freeze-thaw cycling. Four fine-grained soils were prepared at two dry densities corresponding to the upper and lower end of their respective Proctor curves. A laboratory evaluation consisting of grain size analysis, clay mineralogy analysis, standard proctor testing, porosity, water retention, and large scale and small scale frost heave and thaw consolidation observations was undertaken. The specific objectives of this experimentation were:

- 1) To determine geotechnical properties exhibited by samples taken from zones in clay and silt soils which had been exposed to freezing and thawing and from unfrozen soil samples; and

- 2) To relate these geotechnical properties to the soil fabric types described in Chapters 3 and 5;

4.2 Soil characteristics / grain size analysis / Proctor analysis

Four frost susceptible soil types were used in the small scale freezing experiments and one of those, a silt, was also used in a large scale ground freezing experiment. They were obtained from field sites located in proximity to Caen, France. All soil types were considered representative of frost susceptible soils currently classified under the Canadian Department of Transportation grain size criteria.

The grain size curves for the four soils (Figure 4.1) are shown to fall within the limits of frost susceptibility according to the Canadian Department of Transportation Atterberg limit determinations. The Atterberg limit determinations of Tourville silt placed its liquid limit at 46% and its plastic limit at 25%; determinations of Caen silt placed its liquid limit at 34% and its plastic limit at 19%. The determinations of Caen-Moley silt placed its liquid limit at 42% and its plastic limit at 24% while for the Moley clay its liquid limit was placed at 55% and its plastic limit at 29%. All three silts are designated as ML (silt with low plasticity) by the Unified Soil Classification System) while the clay is designated as CH (clay with

high plasticity). Table 4.1 summarises the grain size characteristics and Atterberg limits for each of the soil types.

For the small scale experiments, the clay and silts were compacted to two dry densities corresponding to the upper and lower end of their respective Proctor curves. It was necessary to produce a standard Proctor curve for each of the test soils. The standard ASTM compaction test was used to determine the optimum moisture content at which the given soil has to be compacted in order to attain the maximum dry density. The procedure requires the test soil to be compacted at different dry densities and moisture contents. As moisture content increases (in increments of 2%) the dry density of the soil increases to a maximum and then decreases. This procedure was repeated for the four soil types. Figure 4.2 gives the moisture density curves for the soils. The four frost-susceptible soils were then compacted at their maximum dry densities and at a water content below optimum (10%). Table 4.2 summarises the dry densities to which each of the four soils were compacted.

Table 4.1

	Grain Size Distribution			Atterberg Limits		
	Sand	Silt	Clay	L.L.	P.L.	P.I.
Tourville Silt	15%	59%	26%	46	25	21
Caen Silt	14%	64%	22%	34	19	15
Caen-Moley Silt	7%	55%	38%	42	24	22
Moley Clay	--	40%	60%	55	29	26

Table 4.2

	Max. Dry Density	M.C. %	Lower Dry Density	M.C. %
Tourville Silt	1.57 g/cm ³	22%	1.40 g/cm ³	(14%)
Caen Silt	1.76 g/cm ³	14.5%	1.65 g/cm ³	(10%)
Caen-Moley Silt	1.80 g/cm ³	15.0%	1.55 g/cm ³	(10%)
Moley Clay	1.77 g/cm ³	18%	1.50 g/cm ³	(10%)

Figure 4.2: Moisture-density curves derived
from standard Proctor tests

4.3 Mineralogy of clay size fraction

The grain size analysis of Tourville silt and Caen silt indicates that they contain 20 to 30% clay size fraction. Grain size analysis of Moley clay indicated that in excess of 60% of this clay was comprised of clay size fraction. These observations necessitated a complete mineralogical analysis of the clay size particles to identify whether or not swelling clays such as smectite were present. It was felt that from an understanding of the constituent clay minerals present, possible inferences could be made regarding the development and arrangement of the soil fabrics described in Chapter 5 and their influence on soil permeability described in Chapter 6. The type of clay minerals identified in the soils were also ultimately responsible for determining the method of soil water removal which would be used when preparing the undisturbed specimens for micromorphological analysis (Murphy, 1986).

Samples of the clay size fraction for each soil type were separated by sedimentation. X-ray analysis was then conducted in an attempt to identify whether 1:1 or 2:1 clay mineral types were present.

The standard procedure for X-rays was followed consisting of three series of diffractograms for the analysis of the oriented specimens for each soil type. In the test series a single specimen of Tourville silt, Caen silt and

Moley clay were X-rayed air dried, as is (untreated), at a relative humidity of 50% at 20 °C. A second series of X-rays were then undertaken using a second prepared specimen for each soil type that had been saturated overnight with a 50:50 glycerol - water mixture. A final X-ray series for each soil was then undertaken after these specimens were heated to 550 °C for one hour in a muffle furnace, cooled and X-rayed. According to the d-spacing produced by the three conditions and interpretations conferred by Kodama (Communication, 1995), the 1:1 clay mineral kaolinite is present in all three soil types (Figure 4.3, Tourville silt; Figure 4.4, Caen silt; and Figure 4.5, Moley clay).

The 2:1 swelling clay mineral smectite was identified in both Tourville and Caen silts. A second 2:1 clay mineral, vermiculite, was observed to be present in the Moley clay specimen. D-spacings for the Caen silt also showed the additional presence of the 2:1 clay mineral illite.

4.4 Laboratory procedures: full-scale frost heave experiments

Acting on a proposal from French colleagues, Carleton University's Geotechnical Science Laboratories joined forces in the early 1980's with French scientists and engineers to examine the effects of freezing soils of different textures on a buried chilled pipeline. A suitable controlled environmental facility was available in France. This major

Figure 4.3: X-ray diffraction patterns for Tourville silt:
untreated; glycerol - water; and at 550°C

Figure 4.4: X-ray diffraction patterns for Caen silt:
untreated; glycerol - water; and at 550°C

Figure 4.5: X-ray diffraction patterns for Moley clay:
untreated; glycerol - water; and at 550°C

project provided the opportunity to obtain samples of the Caen silt following exposure to freeze-thaw cycles.

The facility, the Station de Gel, is located at the Centre de Geomorphologie, Caen, France, and was operated under the auspices of Centre National de la Recherche Scientifique, Laboratoire Central des Ponts et Chaussées as well as Energy Mines and Resources, Canada. This totally enclosed, temperature controlled test facility was described in detail (Burgess et al., 1982) when the first Canada-France ground freezing experiment was initiated and again after additional instrumentation was added by Carleton University in 1988 (Patterson et al., 1988) and 1990 (Riseborough et al., 1990). The facility consists of a refrigerated hall 18 m long by 8 m wide and 5 m high situated over a 1.75 m deep trough. The facility was specially prepared for controlling the thermal and hydraulic regimes and for carefully monitoring experimental conditions (Figure 4.6).

The Canada-France ground freezing project was comprised of Canadian and French scientists, engineers, technologists and graduate students in a multi-disciplinary project involving many aspects of soil freezing and thawing. It also looked at the particular effects of freezing soil of different frost heave susceptibilities and different ground thermal conditions.

Between 1982 and 1989 and again between 1990 and 1993, two large-scale studies of soil freezing around a pipeline

Figure 4.6: Longitudinal cross-section of test facility in Caen, France, SS experiment

were carried out. The first, the sand-silt experiment (SS) involved a study of the behaviour of a buried chilled pipeline as it crossed a "textural" transition from frost susceptible silt and non-frost susceptible sand. The SS study consisted of four successive freeze-thaw experiments of varying lengths and different operating conditions. The ambient air temperature was maintained at -0.75°C throughout all four freeze cycles. The temperature of the chilled pipe was varied from -2°C for the first freeze cycle, increasing to -5°C for the second cycle and finally to -5.25°C for the third and fourth cycles. The water table was maintained at 90 cm beneath the soil surface throughout the experiment thus ensuring optimum conditions for ice lens formation in the frost susceptible Caen silt.

The second study, the frozen transition experiment (UP) was conducted between 1990 and 1993 and studied the behaviour of a buried chilled pipeline which crossed a thermal transition from perennially frozen silt to silt exposed to freeze-thaw cycling. The experiment was comprised of two successive freeze-thaw experiments of varying lengths with a pipeline relaxation event occurring between the two cycles. The temperature of the chilled pipe was maintained at -6°C for both freeze cycles while the ambient air temperature was maintained at -4°C . The hydraulic regime was maintained to ensure the water table remained at a level 90 cm beneath the

soil surface throughout the frost heave and thaw consolidation phases of each experiment.

This major project provided the opportunity for soil sampling, carried out at the end of the four freeze-thaw cycles of the SS experiment (White, 1991) and after the completion of the first and third freeze-thaw cycles of the UP experiment (Table 4.3).

4.5 Small scale frost effect experiments

In addition to these full scale frost heave experiments, a series of small scale frost heave / frost effects experiments were carried out between June 1992 and September 1993 with four soil types compacted into special containers placed in the same facility (Plate 4.1).

In order to compare large scale experimental observations of micromorphology and physical properties such as hydraulic conductivity that may result from cryogenic processes, it was necessary to undertake this series of small scale frost effects experiments on four remoulded and compacted soils. One of the soil types, Caen silt, had been utilised in both the SS and UP ground freezing experiments.

Test specimens were compacted into waxed cardboard cylinders measuring 20 cm in height by 10 cm in diameter. The use of a wax cylinder, it was hypothesised, would help reduce (if not eliminate) sidewall effects associated with friction during frost heave and consolidation. The full

Table 4.3: Sampling schedule for full scale SS and UP
ground freezing experiments using Caen silt

Ground Freezing Experiment	Sample Period Along B-B Axis
SS	After Fourth Freeze-Thaw Cycle
UP	After First Freeze-Thaw Cycle
	After Third Freeze-Thaw Cycle

Plate 4.1: Insulated soil specimens installed in water reservoirs in test facility

length of the samples were then insulated (Plate 4.1) to permit one-dimensional freeze-thaw to occur from the surface down. The metal base of the cardboard cylinders were perforated in order to allow free access to water (open system) contained within the reservoir where temperature was maintained just above freezing at 1°C . This ensured that the unfrozen part of the soils remained in a plastic state and that ample water was available to supply growing ice lenses. The small scale frost-effects experiments were then conducted in the totally enclosed, temperature controlled Station de Gel where ambient air temperature was maintained at -4°C . The test specimens had a temperature gradient of $0.20 \pm 0.05^{\circ}\text{C cm}^{-1}$ at the beginning of each freeze cycle. The gradient varied with location as the freezing proceeded because of the different thermal conditions of frozen and unfrozen parts of the sample and its changing length as heaving occurs. At the end of each freezing period (four days) the samples were weighed to verify if any additional uptake of water had occurred and the total amount of heave was measured; the fully insulated small diameter cylinders and their water reservoirs (Plate 4.1) were then removed from the test facility and allowed to thaw from the top down under ambient laboratory air temperatures (15 to 20°C). Thawing generally took one day but was permitted to continue for an additional two days to allow for free drainage and consolidation of the test soils within the cylinders.

Surface elevations were then measured to determine the amount of consolidation and the samples were weighed to verify how much water was lost during the thaw.

Soil sampling and measurements were carried out at the termination of the first, second, third, fifth and tenth freeze-thaw cycles (Table 4.4) for the clay and silt soil types.

4.6 Soil sampling for micromorphological investigations

In order to confirm the hypothesis and preliminary findings reported by White (1991, 1992) and White and Williams (1993), a testing program was designed to investigate the effects of alternating cycles of freezing and thawing on the micromorphology of the clay and silt soils prepared at two different dry densities (Table 4.2) used in the small scale frost effects experiments (Chapter 4), and for a frost-susceptible silt used in the full scale SS and UP ground freezing experiments.

- 1) **Small scale sampling:** Soil sampling was undertaken after the first, second, third, fifth and tenth freeze-thaw cycles of the small scale frost-effects experiment conducted on four fine-grained frost susceptible soils. Undisturbed samples and soil core specimens (Plate 4.2) were taken for micromorphological analysis, hydraulic conductivity and pore size distribution determinations. Sampling was undertaken from both the upper portion of

Plate 4.2: Undisturbed samples from small scale frost effects experiments

Undisturbed sample for micromorphological analysis (a)
Core sample (b) for hydraulic conductivity determinations

each specimen in which freezing took place as well as from the lower portion of each sample where no freezing took place.

- 2) **Large scale sampling:** Vertically oriented Kubiena box samples and soil core samples were taken from Caen silt profiles located in a sample pit situated along the B-B axis 4.4 meters from the silt/sand transition in the SS experiment after the fourth freeze-thaw cycle (Figure 4.7). Sampling was also carried out in the same location in the UP experiment after the completion of each of the first and third freeze-thaw cycles. The sample profiles in the pit were located at the side of the buried pipe and 0.5 m and 1.0 m from the side of the pipe. Careful attention was paid to sampling methodology and procedures outlined in Fox (1993) and every effort was taken to maintain samples in an undisturbed condition (that is, to minimise damage to the samples such as stress cracks). Plate 4.3 depicts both the Kubiena sampling boxes and soil sampling cores used to obtain undisturbed samples of Caen silt. All undisturbed Kubiena box specimens and core samples were placed in storage in a temperature controlled (10°C) and humidity controlled (50%) room at the C.N.R.S., Caen, France and at Agriculture Canada, research Division, Ottawa, prior to undertaking soil water removal and impregnation with polyester resin and measuring

Figure 4.7: Location of sample pit along the B-B axis of the SS and UP ground freezing experiments

Plate 4.3: Undisturbed sampling from SS and UP ground
freezing experiment

Kubiena box specimen (a) located in side of sample pit
Core sample (b) for hydraulic conductivity determinations

hydraulic conductivity, porosity and pore-size distribution.

4.7 Observations of frost heave / consolidation in the SS and UP ground freezing experiments

The two full-scale ground freezing experiments showed that freezing soil results in heaving of the soil and the chilled pipe it contained. Figure 4.8 presents the residual surface deformation of Caen silt at the end of the four freeze cycles of the SS experiment. Figure 4.9 presents the surface heave of Caen silt on day 200 for the first and second freeze cycle of the UP experiment compared to day 200 of the fourth freeze cycle of the SS experiment. Since the chilled pipe traverses soils of differing heave susceptibilities in the SS experiment and from a perennially frozen to seasonally frozen silt in the UP experiment, differential heave of the pipe occurs which has, with each successive cycle, resulted in increasing residual pipe curvature (Figure 4.10 in the SS experiment, and Figure 4.11 in the UP experiment). Cryogenic deformation of the soil structure may be inferred from the residual surface configuration which has become increasingly deformed after successive freeze-thaw cycles for both the SS experiment and UP experiment (Figure 4.9). The changes to relief has resulted from the effects of several processes, including frost heave, thaw consolidation, creep and the mechanical

Table 4.4: Sampling schedule for small scale frost effect experiments of silt and clay

Soil Types	Dry Density	Sampling Periods after Freeze-Thaw Cycles #				
Tourville Silt	Low	1	2	3	5	10
	Maximum	1	2	3	5	10
Caen Silt	Low	1	2	3	5	10
	Maximum	1	2	3	5	10
Caen-Moley Silt	Low	1	2	3	5	10
	Maximum	1	2	3	5	10
Moley Clay	Low	1	2	3	5	10
	Maximum	1	2	3	4	10

Figure 4.8: Residual surface deformation of sand-silt ground freezing experiment after four freeze-thaw cycles (thawing completed)

Please note the changes in scales

modified from: Geotechnical Science Laboratories, 1990, p. 58.

Figure 4.9: Residual surface deformation on day 200 of SS and UP ground freezing experiments (freezing underway)

modified from: Geotechnical Science Laboratories, 1993, p. 54.

Figure 4.10: Residual pipe curvature after fourth freeze-thaw cycle of sand/silt experiment (thaw completed)

from: Geotechnical Science Laboratories, 1990, p. 37.

Figure 4.11: Residual pipe curvature after second freeze-thaw cycle of frozen transition experiment (thaw completed)

modified from: Geotechnical Science Laboratories, 1993, p. 48.

stresses imposed by the pipe and the frozen soil annulus which surrounds the buried chilled pipe.

The ice segregation in this large-scale study has resulted in consolidation via cryosuction of the soil below the frozen layer. This resulted in the progressive lowering of the surface elevation after each thaw consolidation phase compared to the non-frost susceptible soil (sand) in the SS experiment and the artificial permafrost in the UP experiment. The continuing internal deformation of frozen soil produced by small movements of ice, moisture and soil particles which is collectively responsible for creep is thought to be responsible for the irreversible deformation which has taken place.

In spite of the careful attention to maintaining the thermal and hydraulic regimes similarly for cycles two, three and four of the SS experiment and for cycles one and two of the UP experiment, the amount of frost heave experienced by the silt appeared to have increased, with successive cycles, in both experiments. It is theorised that progressive changes in the soil's fabric may be responsible for increasing the frost heave potential of the soil and account for the residual deformation and changes to the thermal and hydraulic properties of the silt.

4.8 Observations of frost heave / consolidation in the small scale frost effects experiments

Similarly for the small scale experiments conducted using the four fine-grained soils, frost heave and thaw consolidation observations were made in an effort to reveal what significant impacts cryogenic alteration of the soil fabric would have.

All four soils irrespective of their dry densities experienced irreversible internal deformations which resulted in changes to their overall height. Figure 4.12 illustrates how, after ten cycles of frost heave and consolidation, all three silts initially compacted at a low dry density on their respective Proctor curves underwent irreversible consolidation. From cycle one through cycle ten the three silts experienced a continuous decline in their surface elevation associated with consolidation of the soil below the frozen layer and compaction of the soil between ice lenses. Conversely, the Moley clay sample was observed to undergo irreversible surface heave. The surface elevation of the Moley clay specimen was 6 mm higher at the end of the tenth freeze-thaw cycle than the original elevation while the Tourville silt was 9 mm lower. The Caen silt was 5 mm lower; the same results presented for the Caen-Moley silt.

Figure 4.12: Residual surface deformation of test soils compacted at low dry density as a function of number of freeze-thaw cycles

The overall trend of irreversible deformation was observed to be repeated for all four soils prepared at their maximum dry densities, albeit to a lesser extent (Figure 4.13). The surface elevations for the Moley clay specimen was 4 mm higher at the end of the tenth freeze-thaw cycle while the silt specimens repeated their deformation via consolidation. Examination of the clay specimens revealed that the clay was stuck to the inner surface of the specimen cylinders. Tourville silt was observed to have a surface elevation of 6.5 mm, lower than its original elevation. Caen silt repeated its deformation of 5 mm and Caen-Moley silt registered an overall decline in surface elevation of only 1.5 mm.

It appears from these observations that the combined effects of consolidation due to cryosuction within the frozen layer which takes place between ice lenses and in the unfrozen zone below are responsible for the lower surface levels. The surfaces have also become increasingly deformed after successive freeze-thaw cycles. Ice segregation in the three silts and the clay specimens has resulted in frost heave in the portion of the sample exposed to freezing. Below the frozen zone consolidation resulted in the overall reduction of sample heights.

Figure 4.13: Sample height of test soils, (maximum dry density) as a function of number of freeze-thaw cycles

4.9 Small scale frost effects experiments: porosity observations

Ice segregation in the four soils has resulted in varying amounts of frost heave and consolidation.

The degree to which freezing and thawing has affected the volume of pores present in the different soil types is reflected by increases in porosity. Sample porosity values (the volume of voids expressed as a percentage of the total volume) are determined from:

$$n = \left(1 - \frac{\rho_d}{\rho_s}\right) \times 100$$

where ρ_s is the average density of soil particles (2.65 g/cm³) and ρ_d is the dry density of the soil. Dry density determinations were made from the core samples used to measure both hydraulic conductivity and soil / water desorption. Figure 4.14 illustrates the porosity values for the upper portion of the soil specimens where freezing took place. Porosity values for Tourville silt increased from 45.6% (unfrozen) to 60.6%, and from 38.8% (unfrozen) to 45.5% for the Moley clay. Porosity values for Caen silt and Caen-Moley silt were observed to increase from 37.7% and 39.9% (unfrozen) respectively to 49.9% for the Caen silt and 47.8% for the Caen-Moley silt after ten freeze-thaw cycles.

Similarly, porosity for the upper portion of the soil columns where freezing took place after compaction to their

Figure 4.14: Porosity of test soils compacted at low dry density as a function of freeze-thaw cycles

optimum dry densities increased for all four soils (Figure 4.15). Tourville silt's porosity values increased between 39.4% (unfrozen) and 55.2%, Caen silt between 33.6% (unfrozen) and 49% and Caen-Moley silt between 32.1% and 46.3%. The Moley clay samples' calculated porosity values were observed to increase from 32% (unfrozen) to 45.4% after ten freeze-thaw cycles.

Overall, freeze-thaw cycles were observed to cause an increase in porosity for all four soils. For the coarser grained soils such as the silts used in this study, increases in porosity may be attributed to both the process of aggregation, and to the creation of new macro pore spaces (planar pores) left behind by intense ice lensing. The combined effects of aggregation and increasing sample porosity in the upper portion of each soil specimen (where freezing took place) resulted in decreasing dry density (Table 4.5) compared to zones of the specimen not exposed to freezing. Changes to porosity for the Moley clay may be attributed to the formation of polygonal shrinkage / desiccation cracks for soils with high clay size fraction such as the Moley clay soil.

Othman and Benson (1993) observed similar behaviour and changes in volume of compacted Wisconsin clay whose grain size is similar to that of the Moley clay used in this research. At the onset of the first freeze, test specimens

Figure 4.15: Porosity of test soils compacted at maximum dry density as a function of freeze-thaw cycles

Table 4.5: Change in dry density in portion of soil sample exposed to freezing (F) as a function of a freeze-thaw cycle.

Soil Type Dry Density (g/cm ³)	Freeze-thaw cycles			
	Unfrozen	1	5	10
Tourville D ₁	1.40	1.19	1.17	1.04
Tourville D ₂	1.57	1.37	1.30	1.32
Caen D ₁	1.65	1.37	1.30	1.32
Caen D ₂	1.76	1.35	1.39	1.35
Caen-Moley D ₁	1.55	1.53	1.41	1.38
Caen-Moley D ₂	1.80	1.52	1.50	1.42
Moley D ₁	1.50	1.45	1.50	1.45
Moley D ₂	1.77	1.53	1.56	1.44

Figure 4.16: Changes in volume as a function of freeze-thaw cycles

from: M.A. Othman and C.H. Benson, 1993, p. 242.

were observed to initially compress (Figure 4.16) but after 5 hours the specimen began to increase in volume. When the soil begins to freeze segregated ice lenses start to form causing expansion, which exceeded the consolidation that took place in the soil. The initial compression was most likely due to the large suction generated below the freezing front which causes the unfrozen soil to contract and expel air from unsaturated pores (Williams, 1964). Thermal contraction may have also been responsible for the recorded decrease in volume.

Water uptake data obtained by weighing the thawed soils contained in the waxed cardboard cylinders at the completion of the thaw phase (Figures 4.17 and 4.18) illustrates the significance of changes to sample porosity for the two initial densities. The reorganisation of soil skeleton components and alteration of existing pore spaces is brought about by intense ice lensing and interlens aggregation (consolidation).

Planar pore spaces created in the new cryogenic fabrics described in Chapter 5 are shaped in such a manner as to better accommodate more soil pore water. From the data it can be inferred that less pore water is being lost during the thaw consolidation phase of each cycle.

Figure 4.17: Water retention for soils prepared at lower dry density as a function of freeze-thaw cycles

Figure 4.18: Water retention for soils prepared at maximum dry density as a function of freeze-thaw cycles

CHAPTER 5

Cryogenic Alteration of Clay and Silt Microstructure: Experimental Findings

5.1 General

In order to evaluate the internal movement and reorganisation of soil fabric components and alteration of pore space distribution, small and large scale laboratory studies of the micromorphology (the study of arrangements of soil constituents and associated pores in soil at a particular time) of four fine-grained soils prepared at two dry densities was undertaken. The specific objectives of this evaluation were:

- 1) To determine the extent to which distinct cryogenic fabrics had developed in four frost susceptible soils after exposure to one, two, three, five and ten freeze-thaw cycles;

- 2) To determine the extent to which distinct cryogenic fabrics had developed in a frost-susceptible soil exposed to full scale ground freezing experiments after the first and third freeze-thaw cycles of the UP experiment and after the fourth freeze-thaw cycle of the SS experiment; and
- 3) To compare cryogenic fabric types and the cryogenic processes responsible for their formation, with cryogenic features observed in soils exposed to seasonal freeze-thaw cycling throughout Canada.

5.2 Sample preparation for micromorphological study

Sample preparation was carried out according to procedures outlined in Murphy (1986) and every effort was taken to maintain all samples in as undisturbed condition as possible (that is, to minimise damage to the samples such as stress and shrinkage cracks).

Microscopic observations of soil fabric and pore space distribution was undertaken after the undisturbed, vertically oriented samples had been impregnated with a polyester resin containing fluorescent dye (Uvitex UB, Ciba-Geigy). Since polyester resins are immiscible in water, water must be removed from the soil prior to impregnation. There are two methods currently used to remove water remaining in the soil prior to impregnating the samples under vacuum with polyester resin. The first method is air drying and the

second, replacement of soil water with acetone. The choice is dependant upon the type of minerals present, specifically clay minerals. Given the presence of the identified swelling clay minerals from the smectite group, found in the Tourville and Caen silts, and vermiculite, found in the Moley clay, soil water replacement with acetone was unsuitable for the purpose of this study due to its effects on soil structure. Murphy (1986) discussed the disadvantages of acetone replacement of soil water for soils in which swelling clay minerals have been identified and how air drying may be used without adversely affecting the structure of the pore space morphology. The polymerised blocks were cut into sections and thin sections (2 x 4 cm) were ground to approximately 20 μm in thickness. The method for sample impregnation and the section preparation is widely documented (Sheldrick 1984, Fitzpatrick, 1984 and Fox et al., 1993).

Thin sections observed under a polarising microscope with plain or polarised transmitted light and incident light, or by a computer image analyser, facilitate the description of the arrangement of soil particles and pores as well as provide information on particular features and how they are interrelated. Characterisations of the pores, their spatial distribution, size and orientation were undertaken (see Chapter 7) and quantitative information was obtained by using computerised image analysis instrumenta-

tion (Bullock and Thomasson, 1979). Analysis of images can also be undertaken using software packages such as IDRISI (White and King, 1995).

Micromorphology of the thin sections was described according to Brewer (1976) and Bullock et al. (1985) and a glossary of micromorphology terminology (Howes and White, 1991). Thin sections were examined with a Leitz Ortholux 11 Pol-Bk polarised microscope at magnification ranging from 6 to 12 x. These provided an indication of the gross morphology that characterise the structure of soil fabric. Each of the thin sections was orientated vertically to the surface.

5.3 Cryogenic fabric observations in small scale frost effects experiments: soils initially at low dry density

Distinct gross morphologies were observed in the small scale frost effect experiments to have developed in samples taken from zones in the upper portion of each soil cylinder where freezing took place. These distinct cryogenic soil fabrics were observed to have developed after only one to five cycles of freezing and thawing.

The dominant morphologies which developed in the four soils compacted to a lower dry density of their Proctor curves are fragmoidic, fragmic and fragmic-porphyroscopic fabrics (Plates 5.2, Tourville silt; 5.5, Caen silt; 5.8,

fabrics (Plates 5.2, Tourville silt; 5.5, Caen silt; 5.8, Caen-Moley silt; and 5.11, Moley clay). These fabrics developed after five freeze-thaw cycles from a granoidic-porphryroskelic intergrade fabric (Plates 5.1, Tourville silt; 5.4, Caen silt; 5.7, Caen-Moley silt and 5.10, Moley clay) which was created through compaction. The fragmoidic fabric designates morphology having horizontally oriented partial and fully accomodated planar pores and coalesced, often elongated, soil units. The fragmic fabric was characterised by elongated, meta vughs with smooth walls. The development of elongated meta vughs was detected by the third freeze-thaw cycle and is attributed to the process of ice lens formation and thaw consolidation. The partial and fully accommodated planar pores and elongated meta vughs were observed in some cases to be interconnected by vertical fractures. Van Vliet-Lanöe (1985) and White and Williams (1993, 1994) noted that soil microfabrics developed directly in response to freeze-thaw cycles and that these distinct morphologies persisted from one freeze-thaw cycle to the next.

The degree to which compaction of the skeleton grains has taken place between the newly created pore space for each soil type is reflected by corresponding changes to sample porosity (Figure 4.14). Maximum planar pore widths of 0.5 to 1.0 mm were observed in the fragmoidic fabric and were observed to decrease in width when the fabric changed

Tourville silt compacted to lower dry density

Plate 5.1:
Unfrozen
Granoidic-
porphyroskelic
fabric

Plate 5.2:
After 5 freeze-
thaw cycles
Fragmoidic
fabric

Plate 5.3:
After 10 freeze-
thaw cycles
Fragmoidic
fabric

All frames are 13.5 mm in length

Caen silt compacted to lower dry density

Plate 5.4:
Unfrozen
Granoidic-
porphyroskelic
fabric

Plate 5.5:
After 5 freeze-
thaw cycles
Fragmoidic
fabric

Plate 5.6:
After 10 freeze-
thaw cycles
Fragmoidic
fabric

All frames are 13.5 mm in length

Caen-Moley silt compacted to lower dry density

Plate 5.7:
Unfrozen
Granoidic-
porphyroskelic
fabric

Plate 5.8:
After 5 freeze-
thaw cycles
Fragmic fabric

Plate 5.9:
After 10 freeze-
thaw cycles
Fragmoidic
fabric

All frames are 13.5 mm in length

Moley clay compacted to lower dry density

Plate 5.10:
Unfrozen
Granoidic-
porphyroskelic
fabric

Plate 5.11:
After 5 freeze-
thaw cycles
Fragmic fabric

Plate 5.12:
After 10 freeze-
thaw cycles
Fragmic-
porphyroskelic
fabric

All frames are 13.5 mm in length

to a fragmic fabric in which pore widths of between 0.1 to 0.25 mm were observed. It can be seen that the cryogenic fabric types created by the tenth freeze-thaw cycle (Plates 5.3, 5.6, 5.9 and 5.12) are quite stable in form and have remained essentially unaltered since they were created between the second and fifth freeze-thaw cycles. It can be theorised that pressure exerted on the pore walls by the growing ice lens and the possible flocculation of colloids by increased salt concentrations in pore water has enhanced the stability of these new fabrics. Parallel to this micro-fabric evolution the amount of frost heave after the first thaw consolidation phase for each of the soil types was observed to undergo increases from the second cycle through to the fifth cycle (Figure 4.12). From the reported microscopic modifications it can be inferred that water migration to the freezing front increased as a result of alterations to the hydraulic conductivity and porosity of the soils. This has been responsible for the progressive rates of frost heave experienced by the soils.

5.4 Cryogenic fabric observations in small scale frost effects experiments: soils initially at maximum dry density

In contrast, compaction of the four soils to their maximum dry densities produced a porphyroskelic fabric characterised by a dense ground mass in the three silts and

in the Moley clay (Plates 5.13, Tourville silt; 5.16, Caen silt; 5.19, Caen-Moley silt and 5.22, Moley clay).

Cryogenic alteration of the porphyroscopic fabric resulted in the formation of both fragmic and fragmoidic fabrics in the test soils (Plates 5.14, Tourville silt; 5.17, Caen silt; 5.20, Caen-Moley silt and 5.23, Moley clay) after exposure to only five freeze-thaw cycles. A banded porphyroscopic intergrade fabric was observed to have developed in both the Caen-Moley silt and Moley clay after exposure to ten freeze-thaw cycles. This reflects a more advanced stage of cryogenic alteration in which planar pore development in these fine-grained soils has become well established.

Such fabric types were interpreted by Pawluk (1988) to form from repeated freeze-thaw cycles. Porosity values for the second set of test specimens prepared at their maximum dry densities were also observed to increase (Figure 4.15), albeit to a lesser extent. It can be seen that the cryogenic fabrics created by the fifth freeze-thaw cycle (Plates 5.14, Tourville silt; 5.17, Caen silt; 5.20, Caen-Moley silt and 5.23, Moley clay) remained intact and were enhanced by an additional five cycles of freeze-thaw (Plates 5.15, Tourville silt; 5.18, Caen silt; 5.21, Caen-Moley silt and 5.24, Moley clay).

Planar pore spacing within the samples was observed to mirror the lens spacing reported by Smith and Williams

Tourville silt compacted to maximum dry density

Plate 5.13:
Unfrozen
Porphyroscopic
fabric

Plate 5.14:
After 5 freeze-
thaw cycles
Fragmic fabric

Plate 5.15:
After 10 freeze-
thaw cycles
Fragmoidic
fabric

All frames are 13.5 mm in length

Caen silt compacted to maximum dry density

Plate 5.16:
Unfrozen
Porphyroskelic
fabric

Plate 5.17:
After 5 freeze-
thaw cycles
Fragmic fabric

Plate 5.18:
After 10 freeze-
thaw cycles
Fragmoidic
fabric

All frames are 13.5 mm in length

Caen-Moley silt compacted to maximum dry density

Plate 5.19:
Unfrozen
Porphyroskelic
fabric

Plate 5.20:
After 5 freeze-
thaw cycles
Fragmoidic fabric

Plate 5.21:
After 10 freeze-
thaw cycles
Banded porphyro-
skelic fabric

All frames are 13.5 mm in length

Moley clay compacted to maximum dry density

Plate 5.22:
Unfrozen
Porphyroscopic
fabric

Plate 5.23:
After 5 freeze-
thaw cycles
Fragmoidic fabric

Plate 5.24:
After 10 freeze-
thaw cycles
Banded porphyro-
skelic fabric

All frames are 13.5 mm in length

(1990) and Othman and Benson (1993). Ice lenses that formed in the first freeze cycle and the planar pores or elongated meta vughs they created were observed to be smaller but more frequent near the top of the specimens. With increasing depth from the surface of the specimens, the number of ice lenses and the planar pores / meta vughs they created were observed to decrease, while their thickness (width) increased. This behaviour can be partially explained if one takes a close look at the rate of cooling. Near the top of the test specimens, the freezing rate and temperature gradient are high and little time is allowed for water to migrate to the freezing front where the ice lenses form. As the freezing front advances down into the specimens the rate of freezing and temperature gradient were reduced and the ice lens formed and grew at a much slower rate. Observations of planar pore distribution indicated quite clearly that much wider and more elongated pores were generally found in the lower extremes of the portion of the specimen where the temperature gradient was at its lowest (0.05 to $0.15^{\circ}\text{C}/\text{cm}$). Vertical fracturing was observed to be prominent between planar pores found in both fragmoidic and fragmic fabric types. Vertical fracturing of soil fabric has been reported by Van Vliet-Lanöe (1985) to result from thermal contraction.

Another important observation again related to ice lens or planar pore spacial distribution was made when looking at

the number of new pore spaces that was being created from one freeze event to the next. As the number of cycles increases, more pore space is created by the increasing number of ice lenses and as Chapters Six and Seven detail, the soils became more permeable and therefore predisposed to water migration.

5.5 Observations of microstructure from full scale SS and UP ground freezing experiments

Distinct gross morphologies were reported by White (1991, 1992) and White and Williams (1993) to have developed in samples of Caen silt after exposure to four freeze-thaw cycles. White (1991) noted that the soil microstructure which developed remained stable. Figure 3.3 (page 67) illustrates the spatial distribution of observed cryogenic fabrics in the soil adjacent to the buried chilled pipeline, as a function of both depth below the surface and distance from the buried chilled pipe for the SS ground freezing experiment after four freeze-thaw cycles. Additional sampling carried out at the Centre de Geomorphologie, Station de Gel, after the first and third UP ground freezing experiment allowed for further insight into the evolution of these distinct fabric types in Caen silt.

The location of segregated ice lenses in the silt profile relative to both the ground surface and at distance from the pipe is shown in Plate 3.3. Ice lens spacing at

the end of the four prolonged periods of freezing for the SS experiment (White, 1992) was observed to vary from closely spaced ice lenses (5 mm to 10 mm apart) in the upper soil layers to thicker ice lenses spaced 20 mm to 30 mm apart at greater depths and distances from the buried chilled pipe. Similarly, planar pore distribution was observed to be similar to the spatial distribution of ice lenses in the soil profile. Planar pores were observed in the fragmoidic fabrics which had developed in close proximity to the pipe (Plate 3.1). The fragmoidic fabric designates morphology having planar pores and separate, coalesced, often elongated soil units; such fabric was interpreted by White (1992) and Pawluk (1988) to form from repeated freeze-thaw cycles. Planar pores were observed in the fragmoidic fabric to be closely spaced, 1.0 mm to 2.0 mm. At depth the spacing between planar pores was observed to range between 2.0 mm to 5.0 mm apart where fragmic fabric was observed to have developed (Plate 3.2, 60 cm below bottom of buried pipe). Fragmic fabric designates morphology having compact aggregates separated by planar pores.

The development of this pattern of spacing is typical of a slow freezing soil characterised by predominately silty texture whose frozen fringe is within the water table. Under steady water supply conditions such as those maintained in both the full scale ground freezing experiments

when the heat flow exceeds the rate of latent heat release the freezing front advanced and initiated new ice lenses.

The observed planar pore spacing for both the small scale frost effects experiments and the full scale SS and UP ground freezing experiments reflects the changing thermal and hydraulic balance at the freezing fronts where ice formed. Spacing was observed to increase as the rate of cooling decreased as a function of depth from the surface, and as a function of number of freeze-thaw events. Figure 5.1 illustrates the position of the 0°C isotherm in the silt on Day 100 of the third and fourth freeze cycle of the SS experiment. The rate of cooling has increased as a function of freeze-thaw cycles and this resulted in changes which took place in the soil's microstructure. Figure 5.2 shows how a similar trend in the rate of cooling as a function of freeze-thaw cycling, has developed in the Caen silt used in the small scale frost effects experiments. Temperature versus depth profiles for the Caen silt showed a progressive decrease in temperature from one freeze-thaw cycle to the next.

From this it is clear that the changes to soil morphology as a function of freeze-thaw cycling appears to affect both the thermal and hydraulic regime of the soil. It may be theorised that changes in thermodynamic properties have resulted from the development of these new cryogenic fabric types.

Figure 5.1: Position of 0°C isotherm on Day 100 for the third and fourth freeze cycle of SS experiment

Figure 5.2: Thermal regime after 36 hours of first, second, third, fifth and tenth freeze-thaw cycle for Caen silt
(small scale frost effects experiments)

5.6 Comparison of cryogenic features dominant in seasonally frozen soils with those produced experimentally

Northern Canadian soils (Turbic Cryosols) are subjected to cryoturbation, a process which makes soil surfaces unstable and is responsible for internal displacement and mixing of materials from different soil horizons (White and Fox, 1995). Distinct patterns of morphology have been described by Fox and Protz (1981), Fox (1983), Smith et al. (1991), Tarnocai et al (1993), Moore et al. (1993) for Turbic Cryosols. Tables 3.3 and 3.4 present a general overview of microstructure which have been observed (Tarnocai et al, 1993) to develop in the periglacial features such as earth hummocks and non-sorted circles (mud boils).

The unvegetated surface horizon which formed in earth hummocks (Figure 3.4) have granular structures beneath them in the Bm horizons that are dominated by granic (Plate 3.6) and granoidic (Plate 3.7) fabrics. Occasionally, there is evidence for plastering of material on the surfaces of the granular units which vary in diameter (1200 to 4000 μm), as well as coalescence with smaller units (Smith et al., 1991).

Pawluk (1988) showed similar granular structure would be produced in till specimens after subjecting them to 100 freeze-thaw cycles. The upper soil horizons of earth hummocks are exposed to numerous freeze-thaw cycles due in part to the extreme temperatures and lack of an insulating layer

of snow. Freeze drying may also contribute to the development of this fabric type. In this environment water present in the surface peds is lost via sublimation. Conversely, non-sorted circles (mud boils, Figure 3.5) are characterised by fragmic, fragmoidic, porphyroskelic and microbanded fabrics which form as a result of intense ice lensing.

Surface horizons of non-sorted circles (mud boils) were observed by Tarnocai et al. (1993) to be dominated by fragmoidic, fragmic, and porphyroskelic fabrics similar to those that were produced experimentally in both the SS and UP ground freezing experiments under similar hydraulic and thermal regimes. This material was observed to be affected by numerous freeze-thaw cycles with ice lens formation and displacement of material. Fragmic, fragmoidic and banded fabric types were identified present in the upper horizons of mud boils where ice lens formation dominated. Plate 5.25 illustrates a fragmoidic morphology in samples taken in close proximity to the permafrost table. This morphology is similar to that which was produced experimentally wherein planar pores and distinct structural units have been produced. Soil pores were observed to be strongly oriented and elongated to the direction parallel to the freezing front reflecting the confining stresses imposed by the overlying frozen soil. Upon thawing, under proper drainage conditions, remnants of these pore types are preserved (White,

Plate 5.25: Fragmoidic fabric

Plate 5.26: Microbanded fabric

Frame lengths are 13.5 mm

both from: C. Tarnocai, C.A.S. Smith, and C.A. Fox, 1993,
p. 86.

1991, Van Vliet-Lane and Dupas, 1992). These pore spaces provide locations for successive sequences of ice lens growth as the permafrost table varies in depth in response to increases or decreases of annual surface temperature. Pores tend to be planar, characteristic of former ice lens formations. Pawluk's (1988), and White and Williams' (1994) experimental studies revealed that the planar pores in the central region of the core samples tended to be strongly oriented parallel to the freezing front. This results in soil fabric which is characterised by microbanding (Plate 5.26) and whose macrostructure is characteristically prismatic.

5.7 Cryogenically induced translocation

Evidence of displacement of both skeleton grains (mineral grains) and plasma (clay size fraction) by inclusions, sorting, rotation and alignments was observed in the microstructure of the fabric types which have been produced experimentally.

Examination of the thin sections revealed that internal movement of skeleton grains (comprised primarily of quartz grains) and plasma had taken place. Present in the thin sections were evidence of clay accumulation on the upper surfaces of planar pores, sorting of soil fabric components to form banded microstructure (isobands) and the rotation and vertical alignment of skeleton grains.

Plate 5.27(a) illustrates how, in the experimentally produced fragmoidic fabric, clay minerals (highlighted by iron oxide staining) (a) have been translocated to the upper surface of a planar pore (b). The accumulation of plasmas was shown by Tarnocai et al. (1993) (Plate 5.27 (b)) to occur above the site of a former ice lens. It can be theorised that plasma-rich melt water has percolated upward (as thaw proceeds from the surface down) and deposited the clay particles out on the upper pore walls. Internal movement of this nature can be inferred from the tendency for accumulations to occupy pore space left behind as ice lenses melted during the thaw consolidation phase at the end of the cycles. Corté (1966) inferred from grain size analysis of soil samples exposed to several cycles of freeze-thaw that there is a tendency for fine particles ($<0.074 \mu\text{m}$) to migrate to the freezing plane.

Internal reorganisation of soil material can be inferred from the tendency for near-vertical to vertical alignment of skeleton grains (Fox and Protz, 1981). The displacement via rotation and realignment of skeleton grains (a) is shown in Plate 5.28 (magnification 25x for samples taken from the full-scale ground freezing experiment).

Kaplan (1985) illustrated that when freezing is from the top down in an open system test such as the one conducted in the full-scale ground freezing experiment and the

Plate 5.27: Translocation of clay-sized particles

(a) Fragmoidic fabric produced experimentally

(b) Fragmoidic fabric in mud boil

Clay accumulations (a) above a planar pore (b)

Frame lengths are 13.5 mm

from: C. Tarnocai, C.A.S. Smith, and C.A. Fox, 1993, p.
162.

Plate 5.28: Realignment of skeleton grains

(a) Frost affected paleosol

Frame is 13.5 mm

from: C. Tarnocai, C.A.S. Smith, and C.A. Fox, 1993, p.
161.

(b) Caen experiment

Frame is 8.5 mm

small scale frost effect experiments, skeleton grains become reoriented when the adfreezing force around them is greater than the forces holding them in place. The total movement experienced by the skeleton grains from their initial position depends upon the heaving rate of the soil and the time required for the 0°C isotherm to penetrate down to a level below the skeleton grains. Corté (1966) distinguished different types of frost sorting, that is, processes by which migrating particles were sorted into zones of uniform particle size. Vertical sorting occurred when freezing and thawing took place from the surface downward, causing larger particles to move upward in relation to the smaller particles. Fox and Protz (1981) suggest that near-vertical or vertical alignment may be in response to advancing irregular freezing fronts. The top of skeleton grain (made up primarily of quartz whose thermal conductivity (K) is $8 \text{ W.m}^{-1} \text{ }^{\circ}\text{C}^{-1}$ compared to the surrounding ground mass and plasma whose combined K value is in the order of $1.2 \text{ W.m}^{-1} \text{ }^{\circ}\text{C}^{-1}$) would be plucked upward by the advancing freezing front while the base remains unfrozen. Depending on the shear strength of the unfrozen soil, the axis of the skeleton grain may undergo rotation with the tendency being toward vertical alignment. Conversely, during the consolidation phase the thawing of the ice lenses would take place after the soil skeleton grains have thawed. The thawed finer material could slump into the space formerly occupied by the

ice lenses thus preventing the return of these larger grains to their original positions.

Particle sorting was observed by White (1992) to be a contributing factor in the formation of micro banded fabric (Plate 5.29). These soil arrangements are similar to the sorted platy structure described by Van Vliet-Lan (1985) as clean, ice-expelled grains appearing between peds. The presence of numerous freezing fronts created by successive ice lens development contributes to particle sorting of the material. Particle translocation during the thaw phase results in fines being concentrated on the upper surfaces of the lenticular units (Fox, 1994).

Banded fabrics were observed to have started to form in the Caen silt after four freeze-thaw cycles in the SS ground freezing experiment. Plate 5.29 shows iron oxide coatings on clay minerals which have formed bands (a) above planar pores (b). Here it is clear that preferential mobilisation of fines to surmount banded sediments and "pressure stress accumulations" (Bunting, 1983) adjacent to the sites of former ice lenses are a major process. The clay fraction, in fact, aids in recording the cryogenic stresses (Van Vliet-Lan and Dupas, 1991) present within soil.

Banded fabric in soil was first described and its origins explained by Kubiena (1938). He recognised this

Plate 5.29: Microband fabric, frost affected paleosol

Clay mineral bands (a) above planar pores (b)

Frame is 13.5 mm

from: C. Tarnocai, C.A.S. Smith, and C.A. Fox, 1993, p. 142.

Plate 5.30: Microband fabric, Caen experiment

Frame length is 13.5 mm

phenomenon as an indication of downward movement of soil solution which, upon drying, formed alternating horizontal layers rich or poor in plasmic substances. In work carried out by Brewer and Pawluk (1975) and Bunting (1983), soils of the Canadian Arctic and subarctic region have been observed to exhibit evidence of banding. The microband fabric (Plate 5.30) which has developed in the Caen silt used in the SS ground freezing experiment and in the three frost susceptible silts used in the small scale frost-effects experiments consists of discrete lens-like microunits oriented more or less parallel to the soil surface and range from 0.3 to 1.0 mm in thickness and 2 to 5 mm in length. The upper portion of the bands appear to contain clay-sized particles.

The presence of microbanded fabrics in the silts is consistent with findings reported by Mermut and St. Arnaud (1981). They noted that the occurrence of microbanding is restricted to soils which are subjected to frost action under hydraulic regimes similar to those maintained in both the full scale ground freezing experiments and the small scale frost-effects experiments, where moisture conditions were kept between field capacity and saturation over the duration of the experiments.

CHAPTER 6

Hydraulic Properties of Frost-Affected Soils: Experimental Findings

6.1 General

In order to evaluate the degree to which clay and silt soil types may undergo alteration of their hydraulic characteristics under freezing and thawing, a laboratory evaluation of hydraulic conductivity and soil water desorption determinations was undertaken. The specific objectives of this evaluation were:

- 1) To find the effect on hydraulic conductivity of freeze-thaw cycling using four soils, each prepared to two dry densities;
- 2) To find the effect on hydraulic conductivity of freeze-thaw cycles on the Caen silt used in the SS and UP ground freezing experiments; and

- 3) To determine the soil water retention characteristics of the same soils and relate the data to porosity data presented in Chapter 4.

6.2 Effect of freeze-thaw on hydraulic conductivity

Dallimore (1984) reported change in hydraulic conductivity of Caen silt after performing detailed analysis of sections of samples exposed to several freeze-thaw cycles. After the first freeze-thaw cycle it was observed that the vertical permeability of the sample increased from $8 \times 10^{-8} \text{ cm s}^{-1}$ to $3 \times 10^{-7} \text{ cm s}^{-1}$. Dallimore suggested that the increase was due largely to an increase in the hydraulic conductivity in the portion of the sample frozen during the test. Intense ice lensing, it is believed, is responsible for structural changes which have created new pathways for increased water flow. Over the past decade several investigators have conducted studies to evaluate the effect of freeze-thaw on the hydraulic conductivity of compacted clays. These findings were summarised by Othman and Benson (1992). The studies involved 14 different clayey soils that varied in composition, plasticity and compaction characteristics. The data indicated that hydraulic conductivity increased by as much as 1400 fold as a result of freeze-thaw cycling. The increase in hydraulic conductivity is largest for clays with the lowest initial hydraulic conductivity. For clays with relatively high initial hydraulic conductiv-

ity ($>1 \times 10^{-10}$ cm/s), the effect of freeze-thaw is minimal. The increase in hydraulic conductivity appears to be similar for a wide variety of natural clayey soils. Othman and Benson (1993) investigated the effect of compaction conditions (moulding water content and compactive effort) and external conditions such as temperature gradient, dimensionality of freezing, number of freeze-thaw cycles and state of stress on the hydraulic conductivity of three compacted clays of different properties. They found that temperature gradient, number of freeze-thaw cycles and state of stress had the largest effect on hydraulic conductivity.

Test results reported by White (1992) (Figure 6.1) indicate that a pattern of hydraulic conductivity similar to the changes reported by Dallimore (1984) had developed in the Caen silt adjacent to a buried chilled pipeline after completion of four freeze-thaw cycles of the SS ground freezing experiment. Hydraulic conductivity values for unfrozen soil at 3.0 m from the test pipe were 10^{-4} cm s⁻¹ (80 cm below surface) compared to higher values (one order of magnitude) 10^{-3} cm s⁻¹ in zones below the buried chilled pipeline and immediately adjacent to the pipe where the most intense segregated ice lensing had been observed by Smith and Williams (1990).

Figure 6.1: Spatial distribution of hydraulic conductivity in Caen silt adjacent to a buried chilled pipeline after four freeze-thaw cycles of the SS ground freezing experiment

from: White, T.L., 1992, p. 76.

6.3 Soil sampling and preparation

Vertically oriented core samples were taken from two portions of each test soil used in the small scale frost effects experiment (Plate 5.1). Samples were taken from the upper portion where freezing of the soil took place, as well as from the lower portion where no freezing took place. Core specimens were also taken from the profiles of sample pits (Plate 5.2) after the first and third freeze-thaw cycle of the UP ground freezing experiment conducted in Caen, France. A description of sample locations is found in section 4.3. Core specimens were sealed and placed in storage in a temperature controlled (15°C) and humidity controlled (50%) room at the C.N.R.S., Caen France and later at Agriculture Canada, Research Division in Ottawa prior to undertaking the measurements of hydraulic conductivity and pore size distribution.

6.4 Hydraulic conductivity determinations

The hydraulic conductivity core samples were prepared and instrumented with a constant head apparatus developed by Klute (1965) and utilised the constant head soil core method (Klute and Dirkson, 1986) to measure the hydraulic conductivity.

Saturated hydraulic conductivity (K_s) is a measure of the ease or ability of saturated porous medium to transmit

water. The parameter is defined by Darcy's Law, which for one-dimensional vertical flow, may be written in the form:

$$q = K_s i$$

where q is the water flux (volume of water per unit cross-sectional area of flow per unit time), i is the hydraulic gradient in the porous medium and K_s is expressed as volume of water per unit cross-sectional area of flow per unit time.

The flow rate through the core was measured by collecting the volume of water in a set period of time (60 second intervals). A total of four flow rate determinations were made for each one and the results were averaged to reduce the effects of variability. Concurrent with the flow rate measurements, the difference in hydraulic head between the top and bottom of the core is determined by measuring the difference in elevation (H) between the water level in the reference tube and the water level in the side arm of the outflow dripper (Figure 6.2).

Using the test data K_s was calculated using:

$$K_s = \frac{4QL}{\pi t H d^2}$$

where Q (ml) is the volume of water collected during time interval, t (sec), L (cm) is the length of sample in the core, H (cm) is the difference in elevation between the

Figure 6.2: Saturated Hydraulic conductivity Test Apparatus

water level in the reference tube and the water level in the side arm of the outflow dripper, and d^2 (cm) is the inside diameter of the core. This yields K_s in units of cm s^{-1} (Reynolds, 1994). Test results are plotted in Figures 6.3 and 6.4 for the two dry densities.

6.5 Results: Small scale experiments

Hydraulic conductivity measurements for the four soils compacted at the lower end of their respective dry density curves were observed to be initially lower after the first cycle in response to consolidation stemming from the cryo-suction induced effective stress on freezing (Figure 4.11). Micromorphological observations indicated that significant reorganising of soil skeleton components occurred in zones of soil located between planar voids created by ice lenses. After the initial freeze-thaw cycle hydraulic conductivity values for cycles two through five progressively increased from $2.45 \times 10^{-4} \text{ cm s}^{-1}$ to $6.27 \times 10^{-4} \text{ cm s}^{-1}$ for Tourville silt, from $8.6 \times 10^{-5} \text{ cm s}^{-1}$ to $4.27 \times 10^{-4} \text{ cm s}^{-1}$ for Caen-Moley silt and from $1.43 \times 10^{-4} \text{ cm s}^{-1}$ to $7.18 \times 10^{-4} \text{ cm s}^{-1}$ for the Caen silt. On the other hand, hydraulic conductivity values for the Moley clay declined from $4.28 \times 10^{-4} \text{ cm s}^{-1}$ to $1.5 \times 10^{-4} \text{ cm s}^{-1}$ due to continuing consolidation of the specimen between cycles one to five. Hydraulic conductivity then slowly increased in value until reaching

Figure 6.3: Hydraulic conductivity of four frost-susceptible soils compacted to a low dry density, as a function of freeze-thaw cycles

Tourville Silt
 + Caen Silt
 * Caen-Molay Silt
 □ Molay Clay

Figure 6.4: Hydraulic conductivity of four frost-susceptible soils compacted to a maximum dry density, as a function of freeze-thaw cycles

Tourville Silt
 Caen Silt
 Caen-Molay Silt
 Molay Clay

its final value of $2.0 \times 10^{-4} \text{ cm s}^{-1}$ after ten freeze-thaw cycles.

Hydraulic conductivity measurements for the four soils compacted at their respective maximum dry density curves were also observed to initially decrease after the first cycle of frost heave and thaw consolidation (Figure 6.3), albeit to a lesser extent. Hydraulic conductivity values for cycles two through five for Tourville silt decreased slightly from $2.41 \times 10^{-4} \text{ cm s}^{-1}$ to $1.4 \times 10^{-4} \text{ cm s}^{-1}$; for the Caen silt increased from $2.7 \times 10^{-5} \text{ cm s}^{-1}$ to $4.0 \times 10^{-4} \text{ cm s}^{-1}$; for the Caen-Moley silt from $7.4 \times 10^{-5} \text{ cm s}^{-1}$ to $3.9 \times 10^{-4} \text{ cm s}^{-1}$; and for the Moley clay by one order of magnitude from $2.9 \times 10^{-6} \text{ cm s}^{-1}$ to $4.1 \times 10^{-5} \text{ cm s}^{-1}$. Increases in hydraulic conductivity may be attributed to the development of horizontally oriented planar pore which are interconnected by vertical pathways created by thermal contraction.

The overall increases in hydraulic conductivity for the three silt soils prepared at two dry densities was paralleled by the development of increasing sample porosity for freeze-thaw cycles two through five. Figure 4.14 illustrates the porosity values for the soils compacted at a low dry density. Tourville silt increased from 45.6% (unfrozen) to over 60% after ten cycles of freeze-thaw. Porosity values for Caen silt and Caen-Moley silt were observed to increase from 37.7% and 39.2% (unfrozen) respectively to 49.9% for the Caen silt and 47% for the Caen-Moley silt.

Moley clay increased from 38.8% (unfrozen) to 45.3 after the completion of the test series.

Similarly, porosity values for four soil types prepared at their optimum dry densities increased for all four soils (Figure 4.15). Tourville silt's porosity values increased from 39.9% (unfrozen) to 55.2%, Caen silt from 33.6% (unfrozen) to 49% and Caen-Moley silt from 32.1% (unfrozen) to 46.3%. The Moley clay porosity values were observed to increase from 32% (unfrozen) to 45.4% after ten cycles of freeze-thaw.

6.6 Hydraulic conductivity results: UP ground freezing experiment

Vertically oriented core samples of Caen silt were taken from zones of three profiles immediately adjacent to the pipe at the end of the first freeze-thaw cycle and from the upper 20 cm after the third freeze-thaw cycle.

All test results are plotted on a cross-section of the sample site locations along the B-B axis. Figure 6.5 depicts the variation in hydraulic conductivity that developed in the Caen silt after exposure to only one freeze-thaw cycle for the UP experiment. Figure 6.6 illustrates the degree to which microstructural alteration of the Caen silt has brought about the changes in hydraulic conductivity to the surface layer of the UP experiment after exposure to

Figure 6.5: Spatial distribution of hydraulic conductivity of Caen silt adjacent to buried chilled pipe after one freeze-thaw cycle of UP ground freezing experiment

Figure 6.6: Spatial distribution of hydraulic conductivity of Caen silt adjacent to buried chilled pipe after three freeze-thaw cycles of UP ground freezing experiment

three cycles of freeze-thaw. Sampling after the third cycle was limited to only the upper 20 cm of the soil.

At the end of the second freeze of the UP experiment a new research initiative (not associated with my research), namely the study of movement of hydrocarbons through freezing and thawing soils was initiated. In this new study, small diameter contamination wells were installed 3 m from the pipe in the frozen silt. This ensured that no contamination of the soils near the buried chilled pipe would take place. As a result of this new study only the upper 20 to 40 cm of the Caen silt was allowed to thaw after the second freeze and was then immediately exposed to a third freeze-thaw cycle.

Overall, the test results indicate a pattern of increasing hydraulic conductivity as a function of freeze-thaw cycles subsequent to the first cycle of frost heave and consolidation. Figure 6.5 illustrates how the Caen silt experiences a full order of magnitude reduction in hydraulic conductivity after completion of the first consolidation phase of the UP ground freezing experiment. These outcomes are quite consistent with the hydraulic conductivity results reported for the four fine-grained soils prepared at two dry densities.

Hydraulic conductivity values for the Caen silt exposed in the near surface zone to three freeze-thaw cycles were observed to have increased by two orders of magnitude to

10^{-3} (Figure 6.6). Hydraulic conductivity values increased by two orders of magnitude from $2.78 \times 10^{-5} \text{ cm s}^{-1}$ to $2.17 \times 10^{-3} \text{ cm s}^{-1}$ at the surface immediately above the buried chilled pipe and from $4.73 \times 10^{-5} \text{ cm s}^{-1}$ to $1.96 \times 10^{-3} \text{ cm s}^{-1}$ 20 cm below surface, again immediately above the pipe. At distances 0.5 m and 1.0 m from the side of the pipe surface hydraulic conductivity values increased, again significantly from $5.34 \times 10^{-5} \text{ cm s}^{-1}$ to $1.94 \times 10^{-4} \text{ cm s}^{-1}$ at .0,5 cm from the pipe and from $7.32 \times 10^{-5} \text{ cm s}^{-1}$ to $5.2 \times 10^{-3} \text{ cm s}^{-1}$ at 1.0 m from the side of the pipe. At a depth of 20 cm below surface the hydraulic conductivity values again consistently increased by one to two orders of magnitude, thus attesting to the significant role that intense segregated ice lensing has on altering the microstructure of the soil after an additional two freeze-thaw cycles.

6.7 Soil water desorption test method

The relationship between the soil water content and soil water suction is a fundamental part of the characterisation of the hydraulic properties of a soil. Soil water desorption data provides information on pore-size distribution which is valuable for characterising soils for unfrozen water content versus temperature, various applications related to drainage, studies of movement of pollutants through freezing and thawing soils and frost heave potential.

Soil water desorption tests are carried out by applying a suction to a specific volume of soil for a time sufficient to allow the pores to drain to a consistent water content at the applied suction. The equilibrated samples are then weighed and this value is used to calculate the water content of the soil at the applied suction.

Following the completion of the hydraulic conductivity determinations of the core specimens taken from the small scale frost effects experiments and the UP ground freezing experiment, samples were prepared for soil water desorption measurements according to methodology described in detail by Sheldrick (1984).

The suction tank provided a suction medium with both high saturated hydraulic conductivity and a high air-entry value. Glass beads with a medium diameter of 30 μm were used as the suction medium for suction pressure heads from 0 to 100 cm of water, and aluminum oxide powder with a medium diameter of 9.5 μm was used for suction ranging between 100 to 224 cm of water.

To achieve desorption of the soil cores, a negative pressure head was applied to the glass bead tank by lowering the constant head burette to give the desired head (Plate 6.1). When the cores had equilibrated for the appropriate amount of time at the desired pressure head, the samples were removed from the tank's suction plate and weighed.

Plate 6.1:
Constant
head
burette

Plate 6.2: Suction tanks

Calculations for size distribution of pores is based on the moisture tension curve. This shows the amount of water in the soil in equilibrium with the suction applied. Pore size calculations are based on the capillary rise equation:

$$h = \frac{2S \cos \Theta}{\rho g r}$$

where h is the height of rise in a capillary tube with radius r , S is the surface tension of water with density ρ ; g is the acceleration due to gravity, and Θ is the contact angle between water and soil (assumed to be zero) (Baver, 1975). This equation simplifies to the expression:

$$r = \frac{(2S/\rho g)}{h}$$

where r is the radius of the pore in millimetres and h is the suction (cm) at which the water in the pore will empty. Larger pores empty at smaller suction. It should be noted that pores in soils generally are highly irregular and ill-defined, so the exact dimension of the pore is not readily expressed. A final cautionary note concerns the presence of swelling clay minerals (Section 4.3) in the samples. Samples prepared for moisture retention measurements are first wetted to saturation and then desaturated. The initial wetting could, it is hypothesised, cause swelling of these clay minerals which would change pore space size. Of

equal concern is the fact that as the desorption test is carried out, the sample (and pores) may shrink.

6.8 Soil water desorption measurements: small scale experiments

Desorption curves (Figure 6.7, Tourville silt and Moley clay compacted at low and high dry density and Figure 6.8, Caen silt and Caen-Moley silt compacted at their respective dry densities) show that variations in water retention exist as a result of the initial degree of compaction prior to freezing.

Figures 6.9 and 6.10 illustrate the influence that freeze-thaw cycling (cycles one through ten) has for Tourville silt. At a tension of -50 cm of water (which corresponds to a pore-size of 60 μm) the Tourville silt water retention increased from 32% to 43% dry weight for the silt compacted at low density after one cycle of freeze-thaw and from 31.5% to 41% dry weight for the silt compacted to its maximum dry density after only one freeze-thaw cycle. After the completion of the tenth freeze-thaw cycle soil water retention was observed to decrease to 40% for the Tourville silt compacted at a low density and increase slightly to 40.3% dry weight for the samples compacted to a higher dry density. The higher water holding capacity of the Tourville silt corresponds well with the observed increase in porosity values (30% to 36.5%).

Figure 6.7: Soil water desorption characteristic of
Tourville silt and Moley clay, unfrozen, compacted to two
dry densities

Figure 6.8: Soil water desorption characteristics of Caen silt and Caen-Moley silt, unfrozen, compacted to two dry densities

Figure 6.9: Effects of freeze-thaw cycles on water retention curves of Tourville silt compacted at low dry density, as a function of freeze-thaw cycles

Figure 6.10: Effects of freeze-thaw cycles on water retention curves of Tourville silt compacted at maximum dry density, as a function of freeze-thaw cycles

Figures 6.11 and 6.12 illustrate the influence that ten freeze-thaw cycles have had on the water holding capacity of Caen silt. The silt when compacted at a low dry density (Figure 6.11) experienced an increase in water retention (at -50 cm) from 27% to 32.5% dry weight and increased to 34% dry weight after five freeze-thaw cycles, then dropped off to 28% after an additional five freeze-thaw cycles. Similarly, water retention characteristics for Caen silt specimens prepared at their maximum dry density (Figure 6.12) also increased from 26% to 35% dry weight after one cycle of freeze-thaw and rose to 36% dry weight by the fifth freeze-thaw cycle before dropping off to 28% dry weight after an additional five freeze-thaw cycles. The residual increases in water retention compare favourably with the residual 4% increases in overall porosity of the Caen silt samples. The large decrease in water retention for Caen silt specimens after another five freeze-thaw cycles indicates that structural deformation has been brought about by cryosuction.

Figures 6.13 and 6.14 illustrate the influence that increasing clay content has had on the water retention characteristics (-50 cm) of the Caen-Moley silt. The silt, which has a 40% clay content when prepared at the two dry densities was observed to experience very little change in water holding capacity, in spite of an overall increase of 6% of porosity. A closer examination of the desorption curve however indicated that most of the water retention

Figure 6.11: Effects of freeze-thaw cycles on water retention curves of Caen silt compacted at low dry density, as a function of freeze-thaw cycles

Figure 6.12: Effects of freeze-thaw cycles on water retention curves of Caen silt compacted at maximum dry density, as a function of freeze-thaw cycles

Figure 6.13: Effects of freeze-thaw cycles on water retention curves for Caen-Moley silt compacted at low dry density, as a function of freeze-thaw cycles

Figure 6.14: Effects of freeze-thaw cycles on water retention curves for Caen-Moley silt compacted at maximum dry density, as a function of freeze-thaw cycles

increases took place between tensions of -100 to -225, corresponding to pore widths of 30 μm and 13 μm . For the Caen-Moley silt specimens prepared at a low dry density (Figure 6.13), water retention at -100 cm, -150 cm and -225 cm increased by 1.5%, 1.25% and 1.75% respectively. Similarly, the Caen-Moley specimens prepared at their optimum dry density (Figure 6.14) also experienced increases in water retention corresponding to tensions of -100 cm, -150 cm and -225 cm. At a tension of -100 after ten freeze-thaw cycles water retention increased by 1% at -150 cm by 1.25% and at -225 cm by 1.25%.

Figures 6.15 and 6.16 illustrate the influence of ten freeze-thaw cycles on Moley clay compacted at two dry densities. Water retention at a tension of -50 cm was observed to increase from 35% to 45% dry weight after ten freeze-thaw cycles for the clay specimens compacted at a low dry density (Figure 6.14) while at the same tension, water retention increased from 29% to 31% dry weight after five cycles of freeze-thaw before falling off to 27% dry weight after ten cycles for the clay specimens compacted at their optimum dry density (Figure 6.14). It can be summarised from this test data that consolidation associated with freezing and segregated ice lens growth is responsible for the clay soil's decreasing water retention.

Soil water desorption measurements were also made for core samples taken at the end of the first UP ground freez-

Figure 6.15: Effects of freeze-thaw cycles on water retention curves for Moley clay compacted at low dry density, as a function of freeze-thaw cycles

Figure 6.16: Effects of freeze-thaw cycles on water retention curves for Moley clay compacted at maximum dry density, as a function of freeze-thaw cycles

ing experiment and after the third freeze-thaw cycle. Hydraulic conductivity values shown in Figures 6.5 and 6.6 show the relative position of the core samples within profiles of the sample pit along the B-B axis of the UP ground freezing experiment.

6.9 Soil water desorption measurements: large scale experiment

At the end of the first and third freeze-thaw cycles of the UP ground freezing experiment vertically oriented soil core samples were taken from three profiles in a sample pit dug next to the buried pipe (Figure 6.17). After hydraulic conductivity determinations had been made the core specimens were transferred to soil water desorption suction tanks and soil water desorption measurements were made.

Figures 6.17 through 6.19 illustrate the influence that a single freeze-thaw cycle has had on the water retention characteristics for the sample profiles adjacent to the side of the pipe, at 0.5 m from the side of the pipe and at a distance of 1.0 m from the side of the pipe. Throughout all three profiles at all sample depths the soil water retention had increased from 26% to values varying between 27% to 32% dry weight at a tension of -50cm. Samples taken at the end of the third freeze-thaw of the UP ground freezing experiment were then measured for soil water retention (Figure 6.20). The data suggests how intense segregated ice lensing

Figure 6.17: Soil water desorption curves after one freeze-thaw cycle (UP experiment). Sample profile adjacent to side of pipe

Figure 6.18: Soil water desorption curves after one freeze-thaw cycle (UP experiment). Sample profile 0.5 m from side of pipe

Figure 6.19: Soil water desorption curves after one freeze-thaw cycle (UP experiment). Sample profile 1.0 m from side of pipe

Figure 6.20: Soil water desorption curves after three freeze-thaw cycles (UP experiment). Surface and 20 cm below surface

—□— 0 cm Side of Pipe	—+— 20 cm Side of Pipe	—*— 0 cm 0.5m From Pipe
—x— 20 cm 0.5 m fm Pip	—x— 0 cm 1.0 m fm Pipe	—▲— 20cm 1.0 m fm Pipe

has been responsible for the alteration of the soil fabric and creation of new pore spaces. At a tension of -50 cm which corresponds to a pore space diameter of 60 μm the water retention was observed to have increased again to between 29% to 33.5% dry weight.

Finally, an examination of soil water desorption curves produced by White (1992) from samples taken at the end of the fourth freeze-thaw cycle of the SS ground freezing experiment confirms that significant structural changes have taken place with the Caen silt. Figures 6.21 (desorption curves for sample cores located at side of the pipe), 6.22 (desorption curves for sample cores located 0.5 m from side of the pipe) and 6.23 (desorption curves for sample cores located 1.0 m from the side of the pipe) illustrate how values of water retention varied from between 30% to 33% dry weight throughout all three sample profiles.

Water holding capacity and higher porosity values within the zones of the soil where intense segregated ice lensing was observed are responsible for creating more macro sized pore spaces ($>10 \mu\text{m}$, Brady, 1984) which are responsible for the soil's higher water holding capacity. Once again, the progressive changes in microstructure from one freeze-thaw cycle to the next have resulted in significant changes to the hydraulic properties of fine-grained soils.

Figure 6.21: Soil water desorption curves after four freeze-thaw cycles(SS experiment). Sample profile at side of pipe

Modified from: White, T.L., 1992, p. 81

Figure 6.22: Soil water desorption curves after four freeze-thaw cycles (SS experiment). Sample profile 0.5 m from side of pipe

Modified from: White, T.L., 1992, p. 82

Figure 6.23: Soil water desorption curves after four freeze-thaw cycles (SS experiment). Sample profile 1.0 m from side of pipe

Modified from: White, T.L., 1992, p. 83.

CHAPTER 7

Computer Image Analysis of Frost-Affected Soils: Experimental Findings

7.1 General

A laboratory study utilising computer image analysis was undertaken to characterise the macro pore size distribution for the silt and clay soils described in Chapter 5. The specific objectives were:

- 1) To determine pore size distribution and macro porosity exhibited by the four soils prepared at two dry densities after exposure to ten freeze-thaw cycles; and
- 2) To relate macro porosity to the porosity values derived from soil water desorption.

7.2 Computer image analysis

Pore space measurements are increasingly used to characterise soil structure because it is the size, shape and

continuity of pores that affect the transport of water through a soil's matrix. In the past, the main methods of determining pore characteristics in soils have been non-optical, eg., water desorption curves, nitrogen sorption and mercury porosimetry (Sheldrick, 1984). Pore spaces are classified morphologically and by size, but their measurement has been restricted by the laborious nature of methods available. These include early techniques such as tracing outlines of voids in block specimens and weighing the tracings (Jongerius, 1963), point counting and the analysis of photograms (Kubiena, 1967).

The introduction of image analysing computers in the early 1970's such as Quantimet 720, Cambridge I.A. and Kontron IBAS made possible rapid and accurate measurement of pore spaces and soil skeleton components larger than 20 μm in diameter in both thin-sections and plastic impregnated soil block specimens. Utilising this new technology soil science has been able to assume a quantitative role in soil survey, supporting field observations with notations of structure, morphology, pedological features and porosity measurements. The measurement of soil porosity is highly valued by soil scientists who are studying the capacity of soil to hold and transmit water.

7.3 Data acquisition: Methodology

This research was carried out using a Kontron IBAS analyser currently in use at Agriculture Canada Centre for Land and Biological Resources Research.

In the Kontron IBAS a black and white photograph of a thin section or the flat surface of a prepared block specimen (Plate 7.1) is scanned with a plumbicon television camera to generate a raster image of 720 lines, each line consisting of 910 discrete pixel squares. The full image is thus composed of over 650,000 pixels but measurements are made within a smaller live video frame 800 columns x 525 lines yielding an image of 420,000 total pixels.

The signal from the camera passes to a detector module and then to a monitor for display. With the Kontron IBAS, soil features such as pores are selected on the basis of their common grey level characteristics, i.e., the instrument is set to measure features such as grey levels with a technique equivalent to density slicing in current image analysis software. The grey level of each pixel is separately assessed by the detector and the signal passed into a series of modules which are used to enhance the image and to spatially measure identified features such as, in the case of this study, pore space distribution and porosity determinations. Figure 7.1 illustrates the process by which dis-

Plate 7.1: Black and white photograph of soil thin section

Pore space depicted in black

Figure 7.1: Discrimination of image

crimination of the image according to the grey level settings take place.

7.4 Image enhancement and processing

Image analysing and processing for the purpose of the study of soil morphology has two somewhat different purposes, the first being to improve the appearance of the image to the human eye for visual analysis, and the second being to enhance the image for quantitative measurement of features such as pore spaces (White and King, 1995). The techniques which are appropriate for each of these tasks are not always the same, but there is considerable overlap (Russ, 1992). The measurement of images generally requires that features be well defined, either by edges or by unique and uniform brightness or colour. Feature distribution within an image is the discrimination between objects and background. Objects are those parts of an image which the viewer wishes to measure, i.e., the evaluation of geometric, textural or densimetric properties. In almost every known method of feature distinction the first step in the process is the decision as to whether to highlight the brighter parts of the image from the background or visa-versa.

Within the Kontran IBAS system, feature distinction is carried out by performing segmentation of the image into its individual phases. It is simply the reduction of a grey level image via thresholding into a binary one, i.e., an

image with two levels, usually black and white. It is only a question of definition, that is, whether or not black or white is to be interpreted as object "phase". Generally, it is the type of measurement, be it pore size, shape or area which defines the appropriate steps to be taken to enhance such images of soil block specimens or thin sections (White, 1991).

Within the Kontron IBAS system it is possible to better define specific features such as edges or unique and uniform brightness or colour. The first step in image processing is to correct some of the defects that may be present in the acquired image. Defects may be present due to imperfect detectors, inadequate or non-uniform illumination or an undesirable viewpoint (Russ, 1992).

In image processing, digital filtering is used to reduce the effects of these defects as well as reduce noise, geometric or radiometric distortion, and to enhance distinct features in an image (textures, edges, etc.). In this study of soil morphology filtering was applied to reduce noise as well as to increase grey level gradients at the edges of features. The overall goal was to enhance the distinction between pore and soil skeleton grains by increasing the homogeneity within each and enhance the boundaries between them.

Digital filtering changes the values of the pixels in the image based on each pixel's previous value and that of

its immediate neighbours. In general, filtering in the spatial domain can be described as:

$$g(x,y) = \frac{1}{(2m+1)(2n+1)} \sum_{k=-m}^m \sum_{L=-n}^n f(x-k,y-L) \times h(k,L)$$

(from KONTRON IBAS, 1981, User's Guide)

where h is a so called filter matrix of the size $(2m + 1)(2n + 1)$. As a result of this equation the resulting grey level $g(x,y)$ of the central pixel is the weighted sum of the grey levels of its neighbourhood points, with the weights being the coefficients of the filter matrix. One of the most commonly used spatial filtering techniques involves passing an $n \times n$ pixel (usually 3×3) window over an image and multiplying the digital number of the central pixel, by some function of all the values covered in the array (Maguire, 1989).

To reduce electronic and radiometric noise, 3×3 moving window mean and median filters were applied to the image generated by the Kontron I.A. (using Kontron software). Subsequently, an edge enhancement filter was applied in both systems to restore grey-level gradients, at edges of pores within the soil matrix which had been blurred by the noise reduction filters.

Plate 7.2 illustrates how the application of the mean and median filters in the Kontron I.A. has resulted in an image with blurred edges. This effect can be at least partially neutralised with the subsequent application of an edge enhancement filter available within both software packages. The application of the edge enhancement filters of the Kontron I.A. successfully produced well defined images (Plate 7.3). In this study the slope of the transition between void spaces (white) has become steeper, resulting in sharper definition between pore spaces and the surrounding soil matrix.

Finally, a colour palette was applied to take advantage of the human ability to distinguish colour contrast better than grey contrast. While the eye can distinguish approximately 30 shades of grey in a monochrome image, it can distinguish hundreds of colours (Dangermond, 1991). Careful selection of a 16 colour palette from amongst the many available colours in a VGA based graphics system can therefore visually enhance differences between features. Using a KONTRON IBAS colour palette, the pore spaces present were defined with an aqua-green colour (Plate 7.4).

An additional feature available within the Kontron IBAS software package allows the user to highlight void space perimeters within the image. In the filtered Kontron image all objects with a grey value $> t$ (shaded objects) were set

Plate 7.2: Application of mean and median filter to image

Pore space depicted in white

Plate 7.3: Application of edge enhancement filter to image

Pore space depicted in white

Plate 7.4: Application of colour palette to image

Pore spaces are depicted in green

to black with the remainder of the image being set to white. Plate 7.5 illustrates how the process of segmentation has achieved better pore space discrimination for the Kontron image.

7.5 Pore size distribution and macro porosity

Pore size distribution patterns (the number of pores plotted against the pore area mm^2) and porosity determinations for each of the soils described in Chapter 6 are presented in Figures 7.2 (Tourville silt, low dry density), 7.3 (Tourville silt, maximum dry density), 7.4 (Caen silt, low dry density), 7.5 (Caen silt, maximum dry density), 7.6 (Caen-Moley silt, low dry density), 7.7 (Caen-Moley silt, maximum dry density), 7.8 (Moley clay, low dry density) and 7.9 (Moley clay, maximum dry density).

Overall, the test results indicate that there is an increase (albeit on a two-dimensional level) in macro pore sizes (pore diameter $> 0.10 \mu\text{m}$) (Brady, 1984) as a function of freeze-thaw cycles. Findings reported by Walker and Trudgill (1983) and Mackie (1987) indicate that it is inevitable that the two dimensional image will underestimate the extent of macro pore development and spatial distribution. In order to overcome this limitation the method requires the rather laborious and time consuming analysis of serial sections in order to produce a three-dimensional representa-

Plate 7.5: Segmentation of pore space within image

Pore spaces are outlined in green, with
larger pores appearing white

Figure 7.2: Pore size distribution of Tourville silt initially compacted at a low dry density, as a function of freeze-thaw cycles

Figure 7.3: Pore size distribution of Tourville silt initially compacted at maximum dry density, as a function of freeze-thaw cycles

Area is in mm^2 ; Count is number of pores

Figure 7.4: Pore size distribution of Caen silt initially compacted at low dry density, as a function of freeze-thaw cycles

Figure 7.5: Pore size distribution of Caen silt initially compacted at maximum dry density, as a function of freeze-thaw cycles

Area is in mm^2 ; Count is number of pores

Figure 7.6: Pore size distribution of Caen-Moley silt initially compacted at low dry density, as a function of freeze-thaw cycles

Figure 7.7: Pore size distribution of Caen-Moley silt initially compacted at maximum dry density, as a function of freeze-thaw cycles

Figure 7.8: Pore size distribution of Moley clay initially compacted at low dry density, as a function of freeze-thaw cycles

Figure 7.9: Pore size distribution of Moley clay initially compacted at maximum dry density, as a function of freeze-thaw cycles

tion of pore continuity. The necessary software for producing a 3-D representation could not be found.

Tables 7.1 (Tourville and Caen silt) and 7.2 (Caen-Moley silt and Moley clay) indicate that overall sample macro porosity values (pore diameter $>0.10\text{ }\mu\text{m}$) continued to increase as a function of freeze-thaw cycles for all four fine-grained soils prepared at their respective dry densities.

Overall, the macro porosity determined by image analysis for the three silts accounted for between 21% to 78% of the soils' total porosity. In contrast, lower macro porosity values of between 12% to 39% were observed to have developed in the Moley clay. The Tourville silt specimens prepared at the lower dry density experienced an initial decrease in macroporosity as a percentage of total porosity from 33.3% to 28.5% in response to the first thaw consolidation phase. But this value increased up to the fifth freeze-thaw cycle, peaking at 57.5% of total porosity before declining slightly to 40.1%. Total porosity was observed to increase 32.8%, from 45.6 to 60.6%. The Tourville silt specimens prepared at their maximum dry density also experienced large increases in the percent of total porosity as macro pore spaces created by ice lenses continued to remain intact from one cycle to the next. The percent of macro porosity (which was responsible for total porosity) increased from 21% to

Table 7.1: Comparison of macro porosity and total porosity for Tourville and Caen silts, as a function of freeze-thaw cycles

Soil/Density	F/T Cycle	Total Porosity	Macro Porosity	Macroporosity as % of Total Porosity
Tourville D ₁	Unfrozen	45.6	15.2	33.3
	Cycle 1	55.2	15.76	28.5
	Cycle 2	54.9	20.38	37.11
	Cycle 3	54.8	25.91	47.2
	Cycle 5	55.7	32.06	57.5
	Cycle 10	60.6	24.08	40.1
Tourville D ₂	Unfrozen	39.4	9.8	24.1
	Cycle 1	49.9	10.18	21.0
	Cycle 2	51.5	13.2	25.6
	Cycle 3	54.5	21.14	38.8
	Cycle 5	52.1	23.65	45.4
	Cycle 10	55.2	34.8	63.0
Caen D ₁	Unfrozen	37.7	17.19	45.6
	Cycle 1	48.1	17.2	35.7
	Cycle 2	50.4	23.8	47.2
	Cycle 3	51.4	28.1	54.6
	Cycle 5	50.9	39.49	77.5
	Cycle 10	49.9	38.12	76.4
Caen D ₂	Unfrozen	33.6	12.74	37.9
	Cycle 1	49.1	14.46	29.4
	Cycle 2	48.3	18.04	37.3
	Cycle 3	47.5	34.5	72.6
	Cycle 5	47.7	34.2	71.7
	Cycle 10	49.0	38.2	77.9

Table 7.2: Comparison of macro porosity and total porosity for Caen-Moley silt and Moley clay, as a function of freeze-thaw cycles

Soil/Density	F/T Cycle	Total Porosity	Macro Porosity	Macroporosity as % of Total Porosity
Caen-Moley D ₁	Unfrozen	39.2	14.6	37.2
	Cycle 1	42.1	12.81	30.4
	Cycle 2	42.6	20.18	47.4
	Cycle 3	41.2	27.77	67.4
	Cycle 5	46.6	19.90	42.7
	Cycle 10	47.8	21.12	44.2
Caen-Moley D ₂	Unfrozen	32.1	19.2	59.8
	Cycle 1	42.4	17.96	42.3
	Cycle 2	41.3	23.73	57.4
	Cycle 3	40.3	20.20	50.1
	Cycle 5	43.2	22.15	51.3
	Cycle 10	46.3	21.30	46.0
Moley D ₁	Unfrozen	38.8	13.18	33.9
	Cycle 1	45.1	5.53	12.3
	Cycle 2	45.1	9.31	20.6
	Cycle 3	44.4	16.37	36.9
	Cycle 5	43.4	9.13	21.1
	Cycle 10	45.3	9.57	21.1
Moley D ₂	Unfrozen	32.0	6.9	21.6
	Cycle 1	42.2	10.30	24.4
	Cycle 2	43.5	9.51	21.8
	Cycle 3	41.8	16.49	39.5
	Cycle 5	41.0	10.81	26.3
	Cycle 10	45.4	8.18	18.0

63% after ten freeze-thaw cycles. Total porosity was observed to increase from 39.4 to 55.2%. Hydraulic conductivity determinations and the overall increases in porosity show the importance of the micromorphological changes. The Tourville silt specimens were observed to have developed a fragmoidic fabric characterised by interconnected planar pores from a granoidic-porphyroscopic intergrade characterised by non-interconnected irregularly shaped pores. Hydraulic conductivity increased from $2.45 \times 10^{-4} \text{ cm s}^{-1}$ to $6.27 \times 10^{-4} \text{ cm s}^{-1}$ after five freeze-thaw cycles for the silt compacted at a low dry density and from $2.41 \times 10^{-4} \text{ cm s}^{-1}$ to $6.9 \times 10^{-4} \text{ cm s}^{-1}$ for the silt when compacted to its maximum dry density.

The Caen silt specimens prepared at the low dry density experienced an initial decrease in percent of macro porosity from 45.6% to 35.7% in response to the first freeze-thaw cycle. Macro porosity values then increased from one freeze-thaw cycle to the next through to the tenth cycles, peaking at 77.5% after five freeze-thaw cycles and levelling off at 76.4% after an additional five cycles. Measurements of the total porosity of the test specimen revealed an overall increase from 37.7 to 49.9%.

The Caen silt specimen compacted to its maximum dry density experienced increases in both total porosity from 33.6% to 49.9% as the macro porosity as a percent of total porosity increased from an initial value of 37.9% to 77.9%

after ten freeze-thaw cycles. Similar to the Tourville silt, the Caen silt was observed to have developed the fragmoidic fabric from the granoidic porphyroskelic intergrade fabric which was created through compaction. Hydraulic conductivity values for Caen silt were observed to increase from $1.43 \times 10^{-4} \text{ cm s}^{-1}$ to $7.18 \times 10^{-4} \text{ cm s}^{-1}$ for the silt compacted at a low dry density and from $2.7 \times 10^{-5} \text{ cm s}^{-1}$ to $1.32 \times 10^{-4} \text{ cm s}^{-1}$ for the Caen silt compacted at its maximum dry density.

The Caen-Moley silt specimens prepared at a low dry density experienced an initial 6.2% decrease in total porosity from 37.2% to 30.4% in response to consolidation. Macro pore space development was then observed to increase from 30.4% to 67.4% of the total porosity by the third cycle before dropping off to 44.2% by the completion of the tenth thaw consolidation phase. It would appear from the micromorphology analysis that the clay aggregate experienced a degree of shrinkage in response to cryogenic suction and that consolidation has taken place within the silt soils. The specimens prepared at their maximum dry density experience an increase in total porosity from 32.1% to 42.4%. Macro pore space development increased between the second and the fifth freeze-thaw cycles, levelling off at 57.4% and decreased slightly to 46.0% after five additional freeze-thaw cycles. Changes in the micromorphology of Caen-Moley silt mirrored the changes in the specimen's total porosity

as the pore spaces continued to increase as a function of freeze-thaw cycles. The original porphyroskelic fabric which characterised the compacted specimens prior to freeze was replaced by the cryogenic fabric, fragmoidic. Hydraulic conductivity values for the silt prepared at the lower dry density increased from $1.43 \times 10^{-4} \text{ cm s}^{-1}$ to $7.10 \times 10^{-4} \text{ cm s}^{-1}$ after three freeze-thaw cycles and increased from $7.4 \times 10^{-5} \text{ cm s}^{-1}$ to $1.87 \times 10^{-4} \text{ cm s}^{-1}$ after only three freeze-thaw cycles.

The Moley clay prepared at a low dry density experienced an increase in both its total porosity (38.8% to 45.1%). Macro pore space development expressed as a percentage of total porosity was observed to increase for cycles one through three, from 12.3% to 36.8% before declining to 21% after ten freeze-thaw cycles. In spite of the inability of the clay to develop significant macro pore space, an overall increase in total porosity was observed. It increased from 38.8% to 45.3% after ten freeze-thaw cycles, most of which is due to association with the development of new micro pore space. Hydraulic conductivity measurements indicated that the clay was undergoing continuous consolidation throughout the experiment. Hydraulic conductivity values declined initially from $4.28 \times 10^{-4} \text{ cm s}^{-1}$ to $1.5 \times 10^{-4} \text{ cm s}^{-1}$ and then increased slowly to $2.0 \times 10^{-4} \text{ cm s}^{-1}$ at the termination of the experiments.

The Moley specimens compacted to their maximum dry densities experienced an overall increase in total porosity from 21.6% to 39.5% as newly formed macro pore spaces remained intact from one freeze-thaw cycle to the next, for cycles one through three. Macro porosity then declined from cycle four through ten and was observed to level off at 26.3%. The test data indicates that consolidation associated with cryogenic induced effective stress on freezing is responsible for the clay soil's decreasing macroporosity.

CHAPTER 8

Summary and Conclusions

8.1 General

The thermodynamic conditions within frozen and unfrozen soil at temperature just below 0°C are such that there are continuing translocations of water, ice and displacements of soil skeleton components and plasma. The dynamic nature of frozen ground has been shown to express itself in microstructural changes which have been observed to take place as a function of freeze-thaw cycles.

The extent to which a soil's microstructure and geotechnical properties undergo cryogenic alteration from one freeze-thaw cycle to the next has provided valuable insights into the mechanics of frost heave and consolidation. Freezing has been shown to more than bond soil and ice particles together. Freezing was observed to alter the arrangement of soil pores and particles, that is, the structure of the soil

and these freezing effects persisted and were enhanced by subsequent freeze-thaw cycles.

Microscopic observations of soil fabrics combined with testing of physical properties have led to a better characterisation of soil behaviour. Ice lens formation and cryosuction have proven to be responsible for the development of cryogenic fabrics with their inherent differences in hydraulic conductivity, porosity and water retention. These studies may lead to a better understanding of how fine-grained soils will interact with Canada's buried infrastructure (comprised of petroleum distribution systems and water and sewage networks) during normal Canadian winters. It is hoped that the reported research will in the future assist in improving our cold climate engineering acumen.

8.2 Summary of results

The major findings of this thesis are summarised as follows:

- 1) Cryogenic alteration of clay and silt microstructure
 - a) Small scale frost effects experiment: low dry density. Distinct cryogenic fabrics developed from a granoidic-porphyrskelic intergrade fabric which had been created through compaction of four fine-grained soils to a low dry density on their respective Proctor curves. The dominant morphologies which developed are

fragmoidic, fragmic and porphyroskelic. The fragmoidic fabric designates morphology having planar pores and coalesced, often elongated meta vughs with smooth walls. The development of meta vughs and planar pores and their interconnection by vertical fractures was detected by the third freeze-thaw cycle and is attributed to the process of ice lens formation and thermal contraction. Porphyroskelic fabrics whose morphology is characterised by a dense ground mass with few or no distinct pores were observed in well defined zones between widely spaced planar pores .

b) **Small scale frost effects experiments: maximum dry density.** Distinct cryogenic fabrics have developed from a uniform porphyroskelic fabric which had been created through compaction of the clay and silt soil types to a maximum dry density on their respective Proctor curves. The dominant morphologies which developed are fragmic, fragmoidic and banded porphyroskelic fabrics. The formation of a fragmoidic and a banded porphyroskelic fabric after only five freeze-thaw cycles illustrates a more advanced stage in cryogenic fabric development in which planar pores in fine-grained soils (compacted at their maximum dry density) have become well established. It can be theorised that pressure exacted on the pore walls by the growing ice lenses and flocculation of colloids by increased salt

concentrations in pore water and their translocation in pore water to the upper and lower surfaces of pore spaces has enhanced the stability of these new fabric types. All these fabric types were observed to persist after exposure to additional freeze-thaw cycling.

c) **Full scale SS and UP ground freezing experiments.** Distinct cryogenic fabrics were observed to have developed from a granoidic-porphyroscopic intergrade fabric which was created through compaction of the Caen silt prior to freezing. The dominant morphology which developed after only three freeze-thaw cycles of the UP experiment and four freeze-thaw cycles of the SS experiment is a fragmoidic fabric. A second fabric type observed was a fragmic fabric characterised by compact aggregates separated by planar pores with widths of up to 0.07 mm.

Spatial distribution of planar pores was observed to be similar to the observed spacing of segregated ice lenses. The development of this pattern of spacing is typical of a slow freezing soil characterised by a predominantly silty texture.

d) **Spatial distribution of planar pores.** The development of patterns of planar pore spacing was observed to be influenced by the thermal gradient across the samples. Near the top of the test specimens

concentrations in pore water and their translocation in pore water to the upper and lower surfaces of pore spaces has enhanced the stability of these new fabric types. All these fabric types were observed to persist after exposure to additional freeze-thaw cycling.

c) **Full scale SS and UP ground freezing experiments.**

Distinct cryogenic fabrics were observed to have developed from a granoidic-porphyroscopic intergrade fabric which was created through compaction of the Caen silt prior to freezing. The dominant morphology which developed after only three freeze-thaw cycles of the UP experiment and four freeze-thaw cycles of the SS experiment is a fragmoidic fabric. A second fabric type observed was a fragmic fabric characterised by compact aggregates separated by planar pores with widths of up to 0.07 mm.

Spatial distribution of planar pores was observed to be similar to the observed spacing of segregated ice lenses. The development of this pattern of spacing is typical of a slow freezing soil characterised by a predominantly silty texture.

d) **Spatial distribution of planar pores.** The development of patterns of planar pore spacing was observed to be influenced by the thermal gradient across the samples. Near the top of the test specimens

frost-effects experiments under comparable hydraulic and thermal regimes.

2) Porosity of clay and silt

The research into physical properties indicates that freeze-thaw cycling brought about significant increases in soil porosity in zones of the sample exposed to freezing after only one freeze-thaw cycle. The largest increase in soil porosity occurred between freeze-thaw cycles one through three. Subsequent freeze-thaw cycles were observed to produce only marginal increases in porosity in all three silts and the clay soil.

Increases in macro porosity are attributed to both the new macro pore spaces (planar pores) created by ice lens formation from one freeze-thaw cycle to the next. Porosity values for Tourville silt compacted to a low dry density increased from 45.6% (unfrozen) to 60.6% and from 38.8% (unfrozen) to 45.5% for the Moley clay. Values for Caen silt and Caen-Moley silt increased from 37.7 and 39.9% (unfrozen) respectively to 49.5% and 47.8% after exposure to ten freeze-thaw cycles.

Similarly, porosity for the four soil types prepared at their optimum dry densities increased for all three silts and the Moley clay. Tourville silt's porosity values increased from 39.4% (unfrozen) to 55.25%, Caen silt from 33.6% (unfrozen) to 49.9% and

Caen-Moley silt from 32.1% (unfrozen) to 46.3%. The Moley clay porosity values increased from 32% (unfrozen) to 45.4% after ten freeze-thaw cycles.

3) Hydraulic properties of clay and silt

The investigation of hydraulic properties indicated that:

a) **Small scale frost effects experiments.** Cryogenic alteration of the hydraulic properties of clay and silt soil types compacted at two dry densities is related to the changes in the microstructure of the fine-grained soils. Hydraulic conductivity of the four soils compacted at a low dry density was observed to initially decrease after the first cycle in response to consolidation. Microscopic observations revealed that pathways through which pore water was normally transmitted were closed by consolidation after the first freeze-thaw cycle. For freeze-thaw cycles two through five, hydraulic conductivity values increased from $2.45 \times 10^{-4} \text{ cm s}^{-1}$ to $6.27 \times 10^{-4} \text{ cm s}^{-1}$ for Tourville silt, from $8.6 \times 10^{-5} \text{ cm s}^{-1}$ to $4.27 \times 10^{-4} \text{ cm s}^{-1}$ for Caen-Moley silt and from $1.43 \times 10^{-4} \text{ cm s}^{-1}$ to $7.18 \times 10^{-4} \text{ cm s}^{-1}$ for Caen silt. Moley clay values declined from $4.28 \times 10^{-4} \text{ cm s}^{-1}$ to $1.5 \times 10^{-4} \text{ cm s}^{-1}$ after five freeze-thaw cycles and increased a full order of magnitude to $2.0 \times 10^{-4} \text{ cm s}^{-1}$ after a subsequent five freeze-thaw cycles.

Hydraulic conductivity values were two orders of magnitude lower, 10^{-5} cm s⁻¹, in the soils with a porphyro-skelic fabric compared to 10^{-3} cm s⁻¹ where fragmoidic and fragmic fabrics characterised the soil.

Hydraulic conductivity measurements for the four soils compacted at their maximum dry densities were also observed to decrease after the first freeze-thaw cycle in response to consolidation. For freeze-thaw cycles two through five, hydraulic conductivity values for Tourville silt increased from 2.41×10^{-4} cm s⁻¹ to 4.0×10^{-4} cm s⁻¹; for Caen silt from 2.7×10^{-5} cm s⁻¹ to 4.0×10^{-4} cm s⁻¹; for the Caen-Moley silt from 7.4×10^{-5} cm s⁻¹ to 3.9×10^{-4} cm s⁻¹; and for Moley clay, one order of magnitude from 2.9×10^{-6} cm s⁻¹ to 4.19×10^{-5} cm s⁻¹.

The overall increases in hydraulic conductivity for the four soil types was consistent with the development of increasing sample porosity characterised by planar pores interconnected by vertical fractures.

b) SS and UP ground freezing experiments

Hydraulic conductivity determinations made from Caen silt which had not been exposed to freezing gave an average 10^{-4} cm s⁻¹. Hydraulic conductivity values were lower, 10^{-5} cm s⁻¹, in zones of the silt where porphyroskelic fabric had developed after exposure to one freeze-thaw cycle of the UP ground freezing exper-

iment. Higher hydraulic conductivities $10^{-3} \text{ cm s}^{-1}$ were observed in zones of the silt where fragmoidic and fragmic soil fabric types were observed after exposure to three freeze-thaw cycles during the UP ground freezing experiment and to four freeze-thaw cycles in the SS ground freezing experiment.

4) Soil water desorption

a) **Small scale frost-effects experiments.** Soil water retention at -50 cm measured in core specimens obtained from the four soil types prepared at two dry densities was observed to increase in value for freeze-thaw cycles one through five. Water retention values increased from 32% (unfrozen) to 43% dry weight after five freeze-thaw cycles for Tourville silt compacted at a low dry density and from 31.5% prior to freezing to 41% dry weight for the silt prepared at its maximum dry density. For Caen silt prepared at a low dry density water retention values increased from 27% (unfrozen) to 34% dry weight; and from 26% (unfrozen) to 35% dry weight for the silt prepared at its optimum dry density. Water retention of the Caen-Moley silt was observed to increase from 28% (unfrozen) to 30% dry weight for the silt at a low dry density and from 27% to 30.5% dry weight for the silt at maximum dry density. Similarly, the water retention for Moley clay

samples at a low dry density increased from 35% to 45% dry weight after five cycles of freeze-thaw and from 29% to 31% dry weight for the clay at maximum dry density.

Water retention decreased slightly for all three silts and the clay samples after exposure to an additional five freeze-thaw cycles (cycles five through ten). This indicates that structural deformation of the soils' skeleton matrix continued to be brought about by cryosuction during the five subsequent freeze-thaw cycles.

b) **SS and UP ground freezing experiment.** Soil water desorption data from the SS and UP ground freezing experiments indicates that a variation in water retention exists between sample locations in zones of the Caen silt where intense ice segregation occurred, and those from zones not exposed to freezing. After only one freeze-thaw cycle of the UP experiment soil water retention increased slightly from 26% dry weight (unfrozen) to values varying between 27 to 32% dry weight at a tension of -50 cm. By the end of the third freeze-thaw cycle of the UP experiment water retention values had increased varying between 29 to 33.5%. The four freeze-thaw cycles conducted during the SS Ground Freezing Experiment produced similar results wherein

soil water retention values increased from 26% (unfrozen) to between 30 to 33%.

5) **Measurement and characterisation of pore morphology by computer image analysis**

a) **Pore size distribution** patterns varied spatially as a function of freeze-thaw cycles. As the number of freeze-thaw cycles increased so too did the number of planar pores created by ice lenses. The new pore space, which at times was interconnected by vertical fractures is responsible for the reported increases in both hydraulic conductivity and porosity that took place primarily between the second freeze-thaw cycle and the fifth. Increases were observed to level off through the subsequent five freeze-thaw cycles.

b) **Macroporosity values** were observed to be highest between 32% to 42% for the three silts and accounted for between 35 to 78% of the total porosity of these fine-grained soils which had developed fragmic and fragmoidic cryogenic fabric types respectively. In contrast, lower macroporosity values of between 5% to 11% were observed in the Moley clay and account for between 12% to 39% of the total porosity of the clay.

6) **Differential frost heave behaviour of fine-grained soils.**

The program of full scale ground freezing experiments and the small scale frost effects experiments have revealed that irregular surface configurations develop in response to frost heave consolidation.

a) **Large scale ground freezing experiment.** After exposure to successive freeze-thaw cycles the frost heave susceptibility of the silt used in both the SS and UP ground freezing experiments was observed to increase. The increasing frost heave experienced by the silt after exposure to two freeze-thaw cycles in the UP experiment and after four freeze-thaw cycles in the SS experiment can be attributed to the changes in soil fabric brought about by intense ice lensing.

b) **Small scale frost effects experiments.** A trend of continued decline in sample height was observed for the three silts prepared at two dry densities after successive freeze-thaw cycles. Freeze-thaw cycling in the three silts prepared at a low dry density was responsible for increasing frost heave from freeze-thaw cycles three through five. Frost heave in the silts prepared at their maximum dry density increased for freeze-thaw cycles four and five. All three silts experienced slight decreases in frost heave after expo-

sure to five additional freeze-thaw cycles. Increasing frost heave was observed in the clay soil prepared at both dry densities, between the second and fifth freeze-thaw cycles, before declining slightly after exposure to five additional freeze-thaw cycles.

8.3 Conclusions and recommendations

The observations reported in this thesis indicate that micromorphology and image analysis techniques can be utilised to make correlations between geotechnical properties and soil microstructure. The investigations have shown how characterisation of soil behaviour, specifically hydraulic conductivity, porosity and water retention can be enhanced by micromorphological observations. Figure 8.1 presents a cryogenic soil fabric index which geotechnical engineers and soil scientists can utilise to estimate hydraulic conductivity and macroporosity as a percentage of total porosity for soil fabric types, some of which can be created after only one freeze-thaw cycle.

This index, it is envisaged, can be used to better characterise the overall behaviour of clay and silt soils, and to improve the reliability of grain size frost susceptibility criteria currently used throughout the world.

While the focus of this thesis has been placed on evaluating changes in geotechnical properties brought about by microstructural changes to clay and silt morphology,

Figure 8.1: Cryogenic soil fabric index

numerous other applications of this research can be foreseen. Micromorphology could be utilised to better assess the dynamic nature of soil freezing and the manner in which soil fabric is modified by abrupt changes to thermal and hydraulic regimes which one might attribute to climatic disturbances or human intervention. Such effects are fundamentally important when a soil becomes a foundation medium for buried infrastructure or when it interacts with pollutants as in the instance of oil spills (Williams et al., 1995).

Finally, it is the author's view that more microstructural and image analysis research should now be undertaken on a wide variety of fine-grained soils which could be exposed to hydrocarbon contamination under different hydraulic and thermal regimes which typically exist in the cold environments. This research would assist in clarifying how hydrocarbon pollutants will modify the microstructure of fine-grained soils exposed to freeze-thaw cycling. This will then enable us to better predict the rates at which oils will migrate through fine-grained soils under a variety of hydraulic and thermal regimes typical of cold environments.

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