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Development of a Frost Heave Test Apparatus

Russell David Lay
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DEVELOPMENT OF A FROST HEAVE TEST APPARATUS

by

Russell D. Lay

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering
Brigham Young University
December 2005
This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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Date .................................................. Mitsuru Saito
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ABSTRACT

DEVELOPMENT OF A FROST HEAVE TEST APPARATUS

Russell D. Lay

Department of Civil and Environmental Engineering

Master of Science

Frost heave damage to roadways costs millions of dollars every year. The need for an improved understanding of the fundamental mechanisms associated with frost heave and methods for efficiently improving frost-susceptible materials prompted the Department of Civil and Environmental Engineering at Brigham Young University (BYU) to undertake a project to design, construct, and verify the functionality of a new frost heave testing apparatus.

Frost heave research has been carried out for more than 75 years. The equipment used to conduct this testing has advanced in accuracy and utility over the years. To establish a background in past and current frost heave research, a survey of 12 frost heave devices, including their construction and capabilities, was performed in this research.

Several design objectives were then delineated, and a nine-specimen frost heave device was designed and constructed to meet the specifications. The apparatus uses one collective heat source and one collective heat sink for all nine specimens. Heave data and temperature data are collected electronically, while the weights of the specimens before and after frost heave testing are measured manually.
Preparatory tests were conducted to confirm the functionality of the data acquisition systems, the uniformity of conditions experienced by all specimens, and the replication of natural roadway freezing conditions. Once preparatory testing was complete, a full-scale frost heave test was performed using the apparatus to investigate the efficacy of cement stabilization in reducing the frost susceptibility of a Montana silt and to validate the functionality of the finished device. Results from the testing indicate that adding 2.0 percent cement actually induces frost heave in excess of that exhibited by the untreated soil. However, additions of 3.5 percent and 5.0 percent were found to be effective in preventing frost heave.

Although minor, recommendations for further improvements to the frost heave apparatus include provisions to further decrease the thermal gradient across the specimen and installation of an automatic temperature control device for the water source.
ACKNOWLEDGMENTS

The author wishes to thank Dr. Spencer Guthrie for his enthusiasm and guidance and the Portland Cement Association for the funding that made this thesis possible. I give my heartfelt thanks to my wife Carmen Lay for her wonderful patience, support, and love and to my darling Eliza for being so excited to see “Dada” every night when I returned home. I would also like to thank the following students whose efforts and camaraderie have contributed significantly to this thesis: Jon Hanson, Brandon Blankenagel, Ben Reese, Ash Brown, Robby Tuttle, Dane Cooley, and Tyler Nelsen.
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CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT
Government transportation engineers have estimated that over half of the costs associated with road maintenance in cold regions can be credited to the effects of freezing and thawing (1). One of the largest sources of this damage to roadways is frost heave and the subsequent thaw-weakening of frost-susceptible pavement layers. As freezing temperatures penetrate frost-susceptible materials, significant amounts of water can be drawn up from underlying soil strata and freeze into layers of ice that usually form just above the freezing front. The expansion of this additional water as it freezes causes the road surface to heave upward. If the road surface heaves unevenly, stresses will develop in the pavement that can cause cracking and poor ride quality. Furthermore, when warmer weather induces thawing from the top down, the frozen soil beneath the thawing front can obstruct vertical drainage and cause supersaturated conditions to develop in the upper roadbed. The excess moisture dramatically reduces soil strength and increases the vulnerability of the pavement structure to damage under traffic loads.

Research investigating the physical mechanisms that cause frost heave and measures that can be taken to mitigate frost damage has been carried out since the 1930s. Much progress has been made by pioneers such as Taber, Penner, and Konrad in gaining an understanding of the physical motivations for frost heave and the conditions required for substantial frost heave to occur. However, in the 75 years that have elapsed since the first frost heave tests were conducted, no procedure has been formulated that can accurately predict the frost heave characteristics of a soil based on common geotechnical tests. Several methods for predicting the amount of frost heave a soil will exhibit have been suggested by individual researchers, but little consensus has been reached in the pavement engineering community as a whole.
During the last several decades, many frost heave test devices have been created. Although the ability of these devices to realistically replicate natural conditions and the quality of the data they produce has improved as computer-controlled environmental chambers and electronic data collection systems have been invented, simplifications inherent in the designs of these devices limit their utility in conducting comprehensive frost heave testing research. A more versatile frost heave testing apparatus is especially needed to facilitate efficient evaluations of the effects of stabilizers on marginal soils and aggregates proposed for use in highway construction. Because methods for preventing frost damage have met with varying results (1, 2, 3, 4, 5, 6), further research performed using better equipment is needed to develop new knowledge about frost heave and techniques for minimizing its detrimental effects on highway infrastructure. Therefore, a project was undertaken in the Department of Civil and Environmental Engineering at Brigham Young University (BYU) to design, construct, and validate a state-of-the-art frost heave testing apparatus.

1.2 OUTLINE OF REPORT
This report contains five chapters. Chapter 1 presents the objectives of the research, and Chapter 2 describes the physical processes associated with the frost heave mechanism and summarizes the characteristics of 12 frost heave devices previously developed by other researchers. Chapter 3 details the development of a new frost heave testing apparatus, including design objectives and construction specifications, and Chapter 4 gives the results of frost heave testing conducted on a frost-susceptible Montana silt treated with three levels of Portland cement. Finally, Chapter 5 presents a summary of the research findings and provides recommendations for further research.
CHAPTER 2
FROST HEAVE IN NATURE AND IN THE LABORATORY

2.1 PROCESS OF FROST HEAVE
This section explains the physical processes associated with frost heave, provides an overview of frost heave classification systems for soils, and briefly discusses the unique conditions that occur in frost-susceptible soils under a roadway.

2.1.1 Introduction to Frost Heave
Frost heave is the vertical displacement of the ground surface caused by the ingress and freezing of subsurface water within the underlying soil strata in response to the penetration of freezing temperatures into the ground. Frost heave occurs in seasonally frozen soils and is therefore associated with a cyclic process of freezing and thawing that can cause annual damage to affected roadways (7).

The two major components of frost heave are in-situ freezing and segregational frost heave. In-situ freezing results from in-place expansion of water as it freezes in the pore spaces between soil particles. When soil freezes quickly, in-situ freezing causes the majority of the heave (8). Although water expands approximately 9 percent in volume when it freezes, this type of frost heave is usually limited to less than about 3 percent of the depth of the frozen zone in unsaturated soils (9).

On the other hand, segregational frost heave, or ice lensing, has the potential to generate very significant frost heaves. For ice lensing to occur, three conditions must be met. First, sustained freezing temperatures must exist. Secondly, free water must be available, and, third, the soil must be frost-susceptible (10). Segregational frost heave occurs in freezing soil strata as frost penetration slows and a quasi-steady-state condition is developed. Water is drawn from the warmer, deeper soils toward the freezing front, where it eventually freezes. Ice lenses begin forming when the rate of heat removal
approximately equals the rate of heat supply at the freezing front. The vertical
displacement of the ground surface depends upon the cumulative thicknesses of the
individual ice lenses. A more detailed discussion of the physical processes associated
with frost heave is given in the next section.

2.1.2 Physical Motivations for Frost Heave
Frost heave results from complex relationships between heat flow, water flow, and stress
distributions in freezing soils as discussed in the following sections.

2.1.2.1 Heat Flow
With the onset of freezing air temperatures above the ground surface, unsteady heat flow
from the warm soil surface to the cold air is initiated. As increasing amounts of heat are
removed from the soil, the freezing front begins to progress downward through the soil
strata. Because air temperatures can drop much faster than soil temperatures, a large
temperature gradient can be created at the air-soil interface. Large temperature
differences cause the frost front to move rapidly downward through the soil nearest the
surface. This rapid progression contributes to frost heave by in-situ freezing of the pore
water between soil particles. In such cases of rapid freezing, no significant accumulation
of water occurs, and the only heaving that occurs is due to the 9 percent increase in the
volume of water as it changes phases from liquid to ice (11).

As soon as the frost front slows and a steady-state system is approximated,
however, segregational frost heave becomes the major source of heave. Steady-state
conditions occur when the energy extracted from the soil in the vicinity of the freezing
front is equal to the energy provided by the underlying soil in the form of latent heat of
crystallization released by the water as it freezes. At this time, further frost penetration
ceases, and ice lensing occurs.

As long as a sufficient water supply is maintained and the thermal gradient
remains constant, the ice lens can continue to grow almost indefinitely. However, the
ability of the soil to supply water to the ice lens diminishes as the water in the region
below the freezing front is exhausted. When the water supply to the growing ice lens
becomes limited, the latent heat of crystallization may not equal the heat being removed
from the soil, causing the frost front to continue downward until the conditions needed to form an ice lens are again met. In this way, a series of ice lenses form perpendicular to the direction of heat flow, separated by layers of frozen soil (12). As the ice lensing progresses downward, successive layers of lenses generally become thicker and more widely separated as shown in Figure 2.1.

FIGURE 2.1 Ice lensing in a Montana silt.
2.1.2.2 Water Transport

The ability of water to move through the soil matrix ultimately controls the growth of ice lenses in freezing soil. The transport of water from the warmer underlying soil towards the frost front is the result of three main mechanisms (13). First, the vapor pressure in warm, underlying soil is greater than in the cooler overlying soil; therefore, vapor flows toward the cooler soil, where it condenses into liquid water and ultimately crystallizes into ice. The second mechanism of water transport is osmosis. As water crystallizes into ice at nucleation points within pore cavities, salts originally dissolved in the freezing water are expelled outwards into the adjacent, unfrozen water, thereby creating a region with higher ion concentrations and a depressed freezing temperature. In an effort to equalize ion concentrations with the pore water system, water migrates towards the frost front from below, where salt concentrations are lower.

The third and usually controlling mechanism is capillary rise, or water flow in response to matric suction gradients within the freezing soil profile. Before the soil begins to freeze, water on the surfaces of the soil particles and in the pore spaces between soil particles forms a network of channels through which water is able to flow. As the freezing front passes through the soil, ice crystals nucleate in the pore water between soil particles. The formation of ice in the pores causes unfrozen water films on the surfaces of the particles to become thinner so that the effective radius of the capillaries forming the unfrozen water network within the freezing soil decreases. With decreasing temperatures, increasing amounts of pore water change to ice, further reducing the liquid water content between soil particles. Although the reduced water content causes a dramatic increase in capillary suction, the permeability of the soil rapidly diminishes as freezing progresses (14). Thus, as liquid water migrates from warmer to colder regions within the soil matrix, and especially as it approaches an active ice lens, its path becomes increasingly tortuous and narrow. At some point, the elevated matric suction levels are no longer able to overcome the reduced permeability, and water flow is terminated, usually at the base of the most recently formed ice lens.

Near the growing ice lens, unfrozen water exists only immediately around the soil particles and consists of adsorbed water molecules and saline water unable to be frozen. A schematic depicting the typical features of a freezing soil is shown in Figure 2.2.
2.1.2.3 Heaving Pressure
As the pore ice grows to form an ice lens, particle-to-particle contact within the soil is disrupted. The weight of the overburden is subsequently transmitted from the soil matrix to the ice-water structure, leading to pressurization of the unfrozen water films along the soil-ice interfaces \((15)\). Additional water can enter the film only when the suction at the interface is sufficient to overcome the counteracting overburden stresses. Because typical overburden pressures in a roadbed range from only 0.4 psi to 3.0 psi, and the pressure required to terminate heave in a silty soil is approximately 11.6 psi, frost heaving can readily occur in frost-susceptible soils given the presence of freezing temperatures and available moisture \((16)\).

2.1.3 Frost Susceptibility of Soils
Several methods have been developed to determine if a soil is susceptible to ice lensing. According to Konrad, three levels of sophistication exist for estimating the frost susceptibility of a soil. Level-one methods are based on the percent of soil finer than a certain size, typically 0.003 in. or 0.0008 in. Level-two methods are based on particle-
size distributions and additional tests regarding the interaction of the soil and water. Level-three methods are based on actual frost heave tests, either in the laboratory or in the field (17).

The most widely used frost classification method is a level-one method developed by the United States Army Corps of Engineers (USACE) that is based largely on the work of Casagrande (7). This method classifies soils into four groups labeled F1 through F4, with F4 being the most frost-susceptible.

Clean sands and gravels are typically too well drained to draw water to a potential ice lens by capillary suction, and clays conduct water too slowly to supply the needs of a growing ice lens (13). Thus, silts, which are fine enough to develop significant matric suction but still coarse enough to allow water to readily permeate the soil matrix, are generally considered to be the most frost-susceptible (18).

2.1.4 Typical Roadway Conditions

In order for the conditions experienced by subsurface soil layers comprising a pavement structure to be simulated, those conditions must be clearly understood. The differences between natural and laboratory conditions account for many of the unsatisfactory results obtained from laboratory experimentation (19).

Most pavement surface layers are underlain by an aggregate base course. The base course is typically a well-graded gravel with a low fines content designed to provide both strength and lateral drainage. While such high-quality base materials are usually non-frost-susceptible, the absence of liquid water within the material allows the freezing front to rapidly penetrate the pavement structure into the subbase and subgrade, which may be frost-susceptible. Figure 2.3 shows a typical cross-section of a flexible pavement.

Based on computations performed using data collected in Sweden, the temperature gradient between the frozen front and the bottom of the lowest ice lens in a typical soil column under a roadway is approximately 0.27°F/in. of soil depth (20). During winter in cold climates, however, the temperature conditions that occur immediately beneath a pavement can vary significantly from those present in the soil beyond the shoulders of the road. Because snow behaves as an insulating layer, plowing the snow from a road surface exposes the pavement to a larger thermal gradient than
would otherwise exist. The larger thermal gradient leads to colder temperatures and increased frost penetration compared to soils located beyond the pavement shoulders (21). As a greater understanding of natural conditions is obtained, the inaccuracies of laboratory testing can be minimized.

2.2 LABORATORY SIMULATION OF FROST HEAVE

In this section, the fundamental components of frost heave devices are discussed, and a history of both traditional and modern methods for frost heave testing is provided. Following the historical discussion, the capabilities and limitations of an ideal frost heave apparatus are summarized.

A list of 12 frost heave devices from Britain, Canada, Finland, Sweden and the United States was assembled in this research (1, 11, 18, 19, 22, 23, 24, 25, 26). Although this list is not an exhaustive compilation of all frost heave devices ever developed in the world, it does provide an accurate representation of the capabilities of both older apparatuses and those of devices built within the last 10 to 15 years.

The general design of frost heave devices has remained the same since the first laboratory frost heave testing was conducted by Taber circa 1930 (22). The method, almost without exception, has been to use a cylindrical sample, provide a water and heat source at the bottom, insulate the sides, and expose the top to freezing temperatures (18, 27). Figure 2.4 shows a schematic of a basic frost heave device.
FIGURE 2.4 Generic frost heave device setup.

Many devices incorporating varying levels of technical sophistication have been used to simulate frost heave. Since Taber created his first frost heave test apparatus, many improvements have been made in testing protocols to facilitate more realistic approximations of road conditions and to enable efficient collection of meaningful test data.

2.2.1 Data Collection

Three parameters that are nearly universally collected in frost heave tests are surface heave, temperature distribution, and water intake (28). A parameter less commonly measured is heaving pressure. Although heaving pressure is an important factor in frost heave testing, it is considerably more difficult to assess than the other values. Consequently, not many frost heave devices are equipped to measure it. Surface heave and temperature profiles can be measured throughout the duration of testing in all 12 frost heave devices, but a satisfactory system to continuously monitor water uptake was not identified in any known frost heave apparatus. The current practice is to instead manually weigh the specimens before and after the frost heave test or at set intervals during the testing.

Data collection and analysis have improved dramatically in recent years with the implementation of computerized data collection systems. With the exception of
Guthrie’s apparatus, all of the surveyed frost heave devices constructed after 1990 were equipped with computerized data collection systems. Prior to this time, most heave data were collected manually or through the use of rotating drum charts. Temperature data have been collected by thermographs and copper-constantan thermocouples since early experiments by Taber. Collection of thermocouple data was most often accomplished through the use of millivolt recorders until computerized dataloggers became common.

2.2.2 Temperature Control
An important characteristic of any frost heave apparatus is its ability to control the thermal gradient across the specimen. The thermal gradient is controlled by the heat source and heat sink used in the device. Documentation describing the features of the 12 frost heave test devices reviewed in this research indicates that a wide range of temperatures has been used in frost heave testing. Table 2.1 gives a summary of the thermal gradients imposed on the specimens in each test device. The devices of Guthrie, Jones, Taber, and USACE use cold air as the heat sink. When cold air is used as the heat sink, the surface temperature of the specimen is warmer than the air in the cold chamber. In cases where the thermal gradients were not explicitly indicated, the thermal gradients were estimated by dividing the change in temperature across the specimen by the length of the specimen.
### TABLE 2.1 Thermal Gradients Created by Various Testing Devices

<table>
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<tr>
<th>Researcher or Agency</th>
<th>Year</th>
<th>Specimen Diameter (in.)</th>
<th>Specimen Height (in.)</th>
<th>Cold Temp (F)</th>
<th>Warm Temp (F)</th>
<th>Thermal Gradient (°F/in.)</th>
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</thead>
<tbody>
<tr>
<td>1. Taber</td>
<td>1930</td>
<td>3.3</td>
<td>6.3</td>
<td>1.40</td>
<td>36.50</td>
<td>5.57</td>
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<tr>
<td>2. Penner</td>
<td>1960</td>
<td>6.0</td>
<td>3.0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3. USACE</td>
<td>1970</td>
<td>5.5</td>
<td>5.0</td>
<td>5.00</td>
<td>39.20</td>
<td>6.84</td>
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<td>4. Loch and Kay</td>
<td>1978</td>
<td>1.5</td>
<td>5.5</td>
<td>19.40</td>
<td>32.90</td>
<td>2.45</td>
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<td>5. Jones</td>
<td>1980</td>
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<td>6.0</td>
<td>1.40</td>
<td>39.20</td>
<td>6.30</td>
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<td>6. Konrad</td>
<td>1980</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>7. Yong and Boonsinsuk</td>
<td>1984</td>
<td>2.0</td>
<td>4.7</td>
<td>14.00</td>
<td>35.60</td>
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</tr>
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<td>8. VTT</td>
<td>1999</td>
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<td>24.80</td>
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<td>2.28</td>
</tr>
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<td>9. Guthrie</td>
<td>2001</td>
<td>6.0</td>
<td>8.0</td>
<td>1.40</td>
<td>41.00</td>
<td>1.82</td>
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<tr>
<td>10. Henry</td>
<td>2001</td>
<td>3.9</td>
<td>5.9</td>
<td>29.48</td>
<td>35.06</td>
<td>0.95</td>
</tr>
<tr>
<td>11. Hermansson</td>
<td>2002</td>
<td>4.8</td>
<td>23.2</td>
<td>21.20</td>
<td>39.20</td>
<td>1.18</td>
</tr>
<tr>
<td>12. Kolisoja</td>
<td>2003</td>
<td>5.9</td>
<td>5.9</td>
<td>26.60</td>
<td>33.80</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Of the 12 devices surveyed, only the devices of Jones and Guthrie provide the heat source to the warm end of the soil via a heated water source. In the other frost heave devices, the water source is separated from the heat source, and a warm plate is used to regulate the temperature of the water as it enters the specimen.

Three types of cooling elements are used to extract heat from the specimens. First, the entire frost heave test apparatus is placed in a cold chamber, allowing the circulation of freezing air to remove heat from the specimen surfaces. Second, a coolant such as propylene-glycol is circulated through a top plate resting on the specimen surface. The third method commonly used incorporates an electric cooling plate such as a Peltier module to remove heat from tested specimens. All three types of cooling elements were reported multiple times by the inventors of the 12 frost heave devices identified in this research, indicating that no clear preference among them has been established by the research community. The use of multiple types of cooling elements also indicates that satisfactory results can probably be achieved by all three methods.
2.2.3 Specimen Size
The difference between thermal gradients occurring in nature and those imposed in a laboratory setting are partly the result of restrictions on the sizes of specimens typically accommodated by laboratory frost heave devices. Shorter specimens require smaller temperature differences between the heat source and heat sink in order to maintain a small thermal gradient. With specimen heights ranging from 3 in. to 23 in. among the 12 frost heave devices reviewed in this research, thermal gradients were highly variable from one apparatus to another. Table 2.1 shows that the thermal gradients for nine of the 12 frost heave devices for which thermal gradients could be calculated are over 5 times greater than that expected in nature.

2.2.4 Water Supply
The various methods of supplying water to tested specimens are further evidence of variability between the 12 frost heave devices. The devices of Henry, Jones, Konrad, Loch, and Penner test specimens that are fully saturated before the frost heave testing begins and ensure that the specimens remain saturated throughout the test by forcing water through the specimens or by maintaining a water table height at the surface of the specimens. The Tampere University of Technology and the USACE test specimens that are initially saturated, but they are not configured to maintain saturation during the test. Instead, a source of free water is provided at the base of the specimen during the frost heave test. The remaining five devices do not require saturation of test specimens but simply allow the specimens a free water source at the bottom during the testing period. The frost heave apparatus of Hermansson is specifically designed to enable testing at different water table heights. An adjustable water table facilitates testing of specimens in both saturated and unsaturated conditions and therefore offers greater utility in simulating various environmental conditions occurring in nature.

An additional consideration in the construction of an apparatus is the ability to supply saline water solutions to the samples. The use of deicing salts throughout northern climates introduces high ion concentrations to the soil pore water as the salts dissolve and diffuse into the ground. The issue of saline water in the frost heave devices
appears to have been largely overlooked in the designs of the frost heave devices surveyed in this research.

2.2.5 Overburden Pressure
Guthrie, Jones, Penner, the Tampere University of Technology, and Yong used no overburden pressure during testing. However, the remaining seven frost heave devices allowed for variable surcharges to be applied, with possible pressures ranging from 0.15 psi to 9.06 psi. In all cases where overburden loads were applied, metal plates were used to produce the desired pressure.

2.2.6 Apparatus Capacity
The number of specimens that can be tested simultaneously in an apparatus also varies significantly. Half of the 12 devices surveyed only accommodate one specimen at a time. A single-specimen apparatus is viewed as a disadvantage when replicates are necessary to statistically substantiate test results. The devices of Guthrie, Henry, Jones, Kolisoja, and Yong accommodate 6, 4, 9, 4, and 2 specimens, respectively. The advantage of multi-specimen capacity is the ability to evaluate multiple specimens in less time. If simultaneous testing of true replicates is to be accomplished, however, the conditions actually imposed on each specimen must be identical. Therefore, great care must be taken to ensure that variability in temperatures, water supply, and other such parameters is minimized.

2.2.7 Desired Capabilities of an Ideal Frost Heave Apparatus
The ideal frost heave apparatus should be designed with the philosophy of closely simulating natural conditions while offering both versatility and accuracy. Considering these overall goals, 12 specific features were identified in this research for inclusion in the frost heave apparatus designed and constructed in this research:

1. A primary objective is to facilitate tight control of the thermal gradient so that it closely approximates the desired conditions. For the purposes of design, a linear thermal gradient between the cold and warm ends of the specimen was chosen.
2. Another universal objective is to measure specimen temperature profiles throughout the frost heave testing. Thermocouples are a natural choice for this task because of their accuracy and ease of use. In a one-dimensional frost heave test, the temperature sensors should be positioned to measure frost penetration rate and to verify that the frost front penetrates on a horizontal plane.

3. Another feature of an ideal frost heave device is the ability to control the rate of frost penetration into the specimen. Ramped freezing tests, or tests that utilize incrementally stepped cold temperatures, are commonly used for this but only approximate the conditions required. Of the 12 devices reviewed in this research, only Hermansson’s device uses a computerized system to automatically control the temperature of the cold cell and thereby adjust the rate of frost penetration so that conditions for lensing can be created as desired (20).

4. The capability to continuously monitor the magnitude of frost heave exhibited by each tested specimen is another important feature. In this way, calculation of heave rates is permitted.

5. The ability to directly measure the heaving pressures developed by tested specimens is another feature that is lacking among the majority of the frost heave devices surveyed in this research. The creation of a method to readily measure the forces exerted by a heaving specimen would provide valuable information as to the heaving pressures generated by the material being tested.

6. The issue of specimen size is another concern for any frost heave test device. When the cold and warm temperatures in a frost heave test are fixed, the height of the specimen directly affects the thermal gradient across the specimen. With the ability to use the full length of a tall specimen for testing, researchers can reduce thermal gradients so that temperature profiles achieved in laboratory testing more closely approximate natural field conditions. In addition to the benefits of a decreased thermal gradient, a large specimen is also useful for investigating the influence of a variable water table height. Therefore, a
large specimen is a desirable feature for frost heave testing. Only Hermansson’s device is capable of holding a tall specimen and investigating the effect of different water table heights (20).

7. In nature, the lateral expansion of a freezing soil is prohibited by the soil adjacent to it. Thus, heave is generally along the vertical axis. In most laboratory situations, however, lateral expansion is rarely fully controlled due to the lack of tensile strength of the specimen container. Therefore, the container or mold in which the specimen is tested must have adequate tensile strength to prevent the occurrence of lateral deformations during freezing.

8. The single most important factor in the ice segregation process is the supply of water to the ice lens. In order to study the effects of water supply to the ice lens, an apparatus that accommodates a variable water table height is advantageous. Therefore, an important feature of an ideal apparatus is the ability to provide a water table high enough to saturate the specimens or low enough to simply supply a constant source of water at the base.

9. The ability to hold potentially corrosive saline solutions is another feature that increases the utility of a frost heave apparatus. The effects of salt water solutions on ice segregation remain largely unappraised by the engineering community. Valuable insight into the role of osmotic suction is to be gained through the use a testing apparatus that is able to accommodate saline solutions.

10. The ability to simulate overburden pressure accurately is another concern that must be addressed in the design of a frost heave apparatus. Various overburden loadings directly simulate the weights of different pavement structures and therefore indirectly simulate various depths within the soil profile. The importance of overburden pressure is further reinforced by research documenting that segregational heave in silts can be terminated by vertical stresses in excess of 11.6 psi (16). Being able to compute the
pressure at which frost heave is terminated for various soils would enable estimation of the depth of soil at which frost heave could not occur.

11. Minimizing the effects of adfreezing between the sides of the mold and the specimen is another feature that is critical in realistically replicating natural conditions. As the frost front progresses downward through the specimen, the free water surrounding the soil particles nearest the mold wall can freeze and adhere to the mold. This adfreezing effectively affixes the sides of the specimen to the mold and creates a dragging force that opposes frost heave of the specimen. Because this force does not occur in natural roadway conditions, an apparatus that minimizes the effects of adfreezing is desirable. The most common remediation method for this problem in many devices has been to lubricate the sides of the container prior to placing the specimen inside it.

12. The ability to test multiple specimens simultaneously is an asset, but only if accomplished properly. If replicate tests are to be performed, identical conditions for all specimens must be maintained, including temperature and water supply provisions.
CHAPTER 3
DEVELOPMENT OF FROST HEAVE TEST APPARATUS

3.1 FORMULATION OF APPARATUS DESIGN
Based on the target objectives listed in Chapter 2, a frost heave test apparatus was designed and constructed at BYU. This chapter describes the specific features incorporated in the device to meet the design objectives, details the construction specifications, and presents the results of several preparatory tests performed to develop a frost heave test protocol.

3.2 DESIGN GOALS
From its inception, the design of the BYU frost heave apparatus was based on the goals of creating a frost heave device that would enable advanced research and high productivity. The apparatus needed to be able to replicate the freezing conditions experienced by soils under a roadway, test multiple specimens at once, and accurately monitor each specimen. Based on these standards, each component was given careful consideration during the design and construction phases of the project. In order to describe the complete frost heave apparatus, this section addresses the six main components of the device separately, including the bath container and water system, external frame, table and collar assembly, specimens and specimen molds, environmental chamber, and data collection system.

3.2.1 Bath Container and Water System
Providing water from one central source was chosen over providing an individual water source for each specimen. Using one water source simplified the design by permitting the use of a single water temperature control device. Therefore, the dimensions for one large bath with sufficient volume to ensure a constant supply of water were determined,
and a square, flat-bottomed basin large enough to hold nine specimens at once was constructed using plexiglass and styrofoam. With a capacity of nine specimens, the device was designed to facilitate simultaneous testing of three replicates of three different specimen types. To allow for high water tables, the walls of the bath were constructed approximately 20 in. high.

Several options for a heat source were considered, but with the communal water supply for all specimens, a communal heat supply via the water in the bath was the most logical choice. Heat tape was chosen because it would act as a line-source of heat to the bathwater and ensure more uniform water temperatures than a point-source water heater. In addition to the use of heat tape, an aquarium water pump was also eventually installed. The water pump provides circulation throughout the device and ensures a uniform water temperature at the base of all specimens.

3.2.2 External Frame
A frame was designed to suspend linear variable differential transformers (LVDTs) over the specimens in such a way that the frame would not rest on the bath or the specimens. Instead, the frame was designed to be placed directly on the floor, ensuring a stable datum for the LVDTs. In order for the specimens to remain accessible through the frame, the top lattice that holds the LVDTs was designed to be easily removed from the sides of the frame. Aluminum was chosen as the frame material because of its light weight and durability. The frame was welded and riveted together to ensure structural integrity.

3.2.3 Table and Collar Assembly
To maintain the position of the specimens constant from test to test and to prevent the specimens from tipping over, a plexiglass table was designed to fit inside the bath, with the surface of the table placed just above the water level.

Collars were designed with the objective of creating an interface between the bath water, the specimens, and the table. The collars were designed using aluminum because of its strength, resistance to corrosion, and high thermal conductivity. Heat conducted through the collar from the bath water prevents freezing of water between the specimen and the table, thereby ensuring that each specimen can be easily removed at the end of a
Another benefit provided by the aluminum collars is that, as the frost front penetrates down through the specimen, the collar effectively confines all lateral expansion in that area and thus avoids damage to the table surface.

### 3.2.4 Specimens and Specimen Molds
Both 4-in. and 6-in. specimen diameters were considered, reflective of current ASTM standards, but the larger size was selected to accommodate larger aggregate sizes within test specimens, thereby producing a closer approximation to field conditions. Steel weights were fabricated for placement on top of each specimen during testing to simulate overburden pressure corresponding to a typical pavement structure. Although only one size of weight was fabricated for this research, various sizes of overburden weights could be produced in the future to simulate other overburden pressures.

### 3.2.5 Environmental Chamber
Like a communal heat source was used in the design of the frost heave apparatus, a communal heat sink was also specified. The entire frost heave apparatus was therefore designed to be placed inside the BYU Highway Materials Laboratory environmental chamber to provide uniform cooling of the tested specimens. Collective cooling in an environmental chamber simplified the design and facilitated full access to the apparatus during testing.

### 3.2.6 Data Collection System
The most important goal of the data collection system was to collect information from the heaving specimens without interfering with the test. That is, the instrumentation needed to be able to collect data without altering the behavior that the specimens would have exhibited in the absence of instrumentation. The data collection system was designed to continuously gather temperature data and axial elongation data throughout the duration of the test so that the magnitudes and rates of frost heave and frost penetration could be assessed.
3.3 CONSTRUCTION OF FROST HEAVE APPARATUS

This section contains a complete description of the final design of the frost heave device. The procedures used in the construction of the device are also discussed. All of the desired features mentioned in Chapter 2 were incorporated into the final design of the apparatus except the ability to measure heaving pressure and the ability to directly control the rate of frost penetration.

3.3.1 Bath Container and Water System

The bath container consists of outer and inner walls separated by a core of insulation. The inner container was constructed of 0.375-in.-thick clear plexiglass sheets, which were glued together with epoxy and screwed together for strength and rigidity. A clear silicone caulking was then also placed along all inside joints to ensure that a watertight bond was formed. The outer walls of the bath were constructed in the same manner as the inner bath walls, except that the plexiglass of the outer wall was 0.5-in.-thick and the caulking was omitted. Two-in.-thick styrofoam sheets were placed between the inner and outer plexiglass walls in order to ensure a minimal heat flow from the bath water to the outside air via the bath container itself. Figure 3.1 shows the profile dimensions of the bath.

A bath fully loaded with nine specimens and filled with 1.75 in. of water holds 10 gallons of water for uptake by the specimens. This amount was found to be sufficient for a continuous supply of water to nine specimens during a 10-day test. The bath water

![FIGURE 3.1 Water bath dimensions.](image-url)
serves two key functions. The most important function of the bath water is to provide a source of free water for the specimens being tested. Second is the role of providing a constant and uniform heat source to all nine specimens, which is accomplished through the use of a submersible aquarium pump and heat tape connected to a variable alternating current device, or variac. The variac controls the heat released by the heat tape by allowing only a specified electrical current into the tape. The configuration of the heat tape and location of the water pump are shown in Figure 3.2. This placement ensures that approximately 20 linear inches of heat tape are within a distance of 4.5 in. of every specimen.

FIGURE 3.2 Configuration of heat tape and placement of water pump.

3.3.2 External Frame
The external frame holds the LVDTs used to measure axial elongation of the specimens during the test. The frame is constructed of 1-in. by 1-in. by 0.125-in. angle aluminum. As mentioned earlier, this material was selected for its light weight, durability, and strength. As illustrated in Figure 3.3, diagonal bracing was provided on three sides of the frame to provide added rigidity.
Diagonal bracing was not placed on the fourth side of the frame in order to allow the frame to slide over the top of the more stationary bath container. The horizontal lattice that holds the LVDT clamps and the LVDTs was constructed of the same angle aluminum as the vertical sides of the frame. The lattice can be removed from the supporting frame structure so that specimens can be easily placed into and removed from the bath. Attached to the horizontal lattice are the LVDT rods and clamps. The clamping assembly used to hold an LVDT over the surface of a specimen is shown in Figure 3.4. A set screw is used to adjust the rod vertically to accommodate various specimen heights and various LVDT sizes. Another screw is used to secure the LVDT into the clamping assembly.
3.3.3 Table and Collar Assembly
Both the surface and the legs of the specimen holding table were constructed of the same clear 0.5-in.-thick plexiglass that was used to fabricate the outer wall of the bath. The table surface was cut using a computer-controlled water jet as depicted in Figure 3.5. The function of the table is to hold the specimens upright and ensure proper horizontal spacing between the specimens. Therefore, precision manufacturing was utilized to ensure that the specimen holes were placed exactly as desired.
FIGURE 3.5 Water jet used to cut table surface.

Specimen collars serve a threefold purpose. First, they function as a heat conductor between the water and the specimens. Second, they provide a seal between the outer air and the air below the table surface. The third function of the collars is to protect the table surface by confining the lateral expansion of the specimens if the frost front progresses below the level of the table. The collars were constructed from a 0.375-in.-thick sheet of aluminum and a 0.375-in.-thick-walled aluminum pipe with a 6.125-in. inner diameter. Figures 3.6 and 3.7 show the pipe being cut and the assembly of the collars.

The table surface is covered with a 2-in.-thick sheet of styrofoam cut with holes that allow for the specimens to be inserted through and removed from the table. This table insulation minimizes heat loss into the environmental chamber from the water bath beneath the table surface.
3.3.4 Specimens and Specimen Molds

The frost heave apparatus was designed to accommodate 6-in.-diameter specimens. A minimum specimen height of 9 in., which is exactly twice the height of standard ASTM specimens, was chosen to facilitate straightforward compaction of disturbed specimens, although specimen heights up to 18 in. may be accommodated by the apparatus. For 9-in.
specimens, the material to be tested is compacted into standard 12-in.-tall by 6-in.-
diameter plastic molds, leaving 3 in. between the top of the mold and the surface of each specimen. The molds have seven 0.125-in.-diameter holes drilled into the bottom to allow for water uptake. This feature is illustrated in Figure 3.8. At the bottom of each specimen, between the compacted soil and the bottom of the mold, a filter paper prevents the ejection of fines into the bath water.

Three specimens are instrumented with seven thermocouples each during a frost heave test. The positions of the instrumented specimens within the apparatus are changeable; however, one corner specimen and one side specimen should always be included. The specimens are instrumented with thermocouples at 1-in. intervals from the soil surface down to a height of 3 in. from the bottom. Below the water level, the soil temperature is assumed to be equivalent to the water bath temperature. The thermocouples are inserted through the sides of the specimens to a depth of approximately 1 in. to ensure a temperature representative of the soil.

In order to maintain horizontal penetration of the frost front, lateral insulation is placed around each specimen prior to testing. The insulation consists of two types of flexible, closed-cell, foam rubber pads. The inner insulation is somewhat thinner and more flexible than the outer insulation. Both types of insulation sheets are 10 in. wide by

![FIGURE 3.8 Typical specimen molds with holes in the base for water uptake.](image)
72 in. long and attached end to end, forming one sheet that is 10 in. wide by 144 in. long. Each specimen is tightly wrapped with the flexible insulation closest to the specimen, allowing the soft foam rubber to conform to any irregularities on the surface of the specimen molds, such as the thermocouple wires extending out of the sides of the specimen. The harder foam rubber provides additional insulation and protection to the specimens. Figure 3.9 shows the two types of insulation being taped together, and Figure 3.10 shows an instrumented specimen fully wrapped in lateral insulation with an elastic band to keep the wraps in place.

FIGURE 3.9 Two types of lateral insulation being taped together.
The overburden weights were cut from a 6-in.-diameter steel rod and then symmetrically drilled until they weighed exactly 10 lb. The weights were then sandblasted clean, etched with liquid bluing, and treated with oil to prevent rust during frost heave testing. Figure 3.11 shows a schematic of a fully instrumented specimen as it would appear in a testing situation.
3.3.5 Environmental Chamber

The environmental chamber in the BYU Highway Materials Laboratory houses the entire frost heave apparatus, with the exception of the computers used to record test data. The environmental chamber controls the temperature of the chamber, as calculated during testing conducted in this research, to within 1.04°F of the target temperature. Fans within the chamber circulate the air during the test to ensure that all specimens are under the same surface temperature conditions. Figures 3.12 and 3.13 show the exterior and interior of the environmental chamber, respectively.

![FIGURE 3.12 Exterior of environmental chamber.](image-url)
3.3.6 Data Collection System
The data collection system electronically records two types of information during a frost heave test. The thermocouples collect temperature information, and the LVDTs collect measurements of axial elongation, both on 10-minute intervals. The temperature information is recorded by a datalogger and is downloaded at the end of the test using a laptop computer. The length measurements are made by LVDTs and are recorded using commercial software on a portable desktop computer as shown in Figure 3.12.

3.4 PREPARATORY TESTING OF THE APPARATUS
After construction of the frost heave apparatus was completed, a series of preparatory tests were conducted. These tests had three main objectives. The first objective was to minimize the temperature differences between conditions in the laboratory and those known to occur in the field, and the second was to verify the functionality of the device. The third objective of the preparatory testing was to establish a testing protocol that could be used as a standard for future tests. These preparatory tests addressed multiple issues about the use of the apparatus necessary to establish a frost heave test procedure. This section gives a detailed account of each test.
3.4.1 Preparatory Test 1

The two main purposes of the first test were to establish a point of reference from which subsequent tests could be judged and to become familiar with the use of the thermocouples, LVDTs, and data acquisition system. This test was conducted with the air temperature at 23°F and with three specimens in place. Styrofoam insulation was used to completely cover the remainder of the table, including the holes where other specimens would normally be placed. Eighteen ft of the heat tape was submerged in the water and directly connected to a 115-V electrical outlet; the variac was not utilized to reduce the electrical power to the heat tape during this test.

Although the LVDTs appeared to function properly throughout the test, the thermocouple data were the focus of the analysis. Ten thermocouples were employed in the testing to monitor the air and specimen temperatures. Each specimen was instrumented with three thermocouples that were inserted through holes in the plastic mold. One thermocouple was placed just under the overburden weight at the specimen surface, another at mid-height, and the last near the water level. Due to the effectiveness of the bath and table insulation, the temperature of the bath water actually increased during the test as illustrated in Figure 3.14.

![Thermocouple readings from preparatory test 1.](image)

**FIGURE 3.14 Thermocouple readings from preparatory test 1.**
3.4.2 Preparatory Test 2

Due to the increasing water bath temperatures exhibited during preparatory test 1, a method to reduce the energy output on the heat tape was needed. To decrease the electrical current through the heat tape, a variac was installed between the electrical outlet and the heat tape. Identifying a variac setting that would yield a sufficiently low but constant water temperature was the main objective of the second test.

As in preparatory test 1, this test was performed with three specimens and with the air temperature at 23°F. Only 16 ft of heat tape was submerged in the water for this test, and the voltage in the heat tape was decreased to 75 V. Two additional thermocouples were utilized in this test to measure the temperature of the bath water in different locations, bringing the total number of thermocouples to 12. After 24 hours of testing, the temperature readings indicated that freezing temperatures would not be able to penetrate the specimens, and the test was ended early.

3.4.3 Preparatory Test 3

The two main objectives of the third test were to lower the water temperature and to investigate the time required before thermal equilibrium is reached. For this test, the electrical source for the heat tape was reduced to 45 V; however, in all other respects, the third preparatory test was identical to the second. At the conclusion of this test, a minimum water temperature of 37.2°F was achieved, and specimen surface temperatures reached 31.5°F. Nonetheless, the frost was still unable to penetrate the specimens; as shown in Figure 3.15, no other thermocouples indicated freezing temperatures.

Several issues of timing were also addressed during preparatory test 3. By the end of preparatory test 3, a trend became clear that thermal equilibrium, or a condition close thereto, was achieved after the test had been running for 100 hours. This rough standard has been supported by subsequent testing. Once thermal equilibrium was achieved, the frost front penetrated no further into the specimen, and a steady-state condition was achieved. The timeline of a standard test for the frost heave apparatus is provided in Figure 3.16. With a constant heave rate not established until 6 days into the test, 4 additional days of data collection seemed appropriate. Another observation from this test was that spatial variation in the bath water temperature was approximately
1.62°F, which raised concerns about the uniformity of the test conditions for simultaneous evaluations of multiple specimens.

FIGURE 3.15 Thermocouple readings from preparatory test 3.

FIGURE 3.16 Timeline of a typical frost heave test.
3.4.4 Preparatory Test 4

The main goal of the fourth test was to evaluate whether or not the frost front was horizontal as it penetrated the specimen. This was accomplished by using multiple thermocouples to create a two-dimensional image of the frost front. Additionally, this test showed the behavior of the soil at heave initiation for the first time.

In this test, the voltage was held at 45 V, the air temperature was reduced to 10.4°F, and all nine test locations within the frost heave test apparatus were filled with soil specimens. The temperature reduction was made with the intent of increasing the rate of heat removal and therefore forcing the freezing front into the soil. With this configuration, the frost front penetrated the entire specimen. Fifteen thermocouples were used in this test, 12 of which were inserted into one specimen at various heights and at various distances from the central axis of the specimen.

Data collected from the single specimen with 12 thermocouples were evaluated to verify that the lateral insulation is sufficient to cause the frost front to penetrate into tested specimens on a horizontal plane, as it would in nature. Based on the temperature measurements recorded through time, an image of the shape of the frost front was constructed as shown in Figure 3.17. During most of the test, the frost front was slightly concave down. This indicates that the specimens were slightly colder near the edge and that the lateral insulation has somewhat lower insulating properties than desirable.
Preparatory test 4 was the first test conducted with all 9 specimen locations filled. Having all test locations filled with specimens demonstrated the effectiveness of the table insulation. The amount of heat lost by each specimen was significantly higher than the heat lost by the table insulation that was used to cover a specimen hole in the absence of a specimen. Therefore, the temperature of the bath water changes with the addition or removal of specimens. For consistency to be maintained from test to test, an equal number of specimens must be placed in the apparatus each time a test is performed. For this reason, all subsequent frost heave tests were conducted with a fully loaded apparatus.
3.4.5 Preparatory Test 5

The foremost objective of preparatory test 5 was to refine the settings of the variac and the environmental chamber air temperature in order to minimize the thermal gradient and to control the depth of frost penetration within the soil. A second objective was to evaluate the efficacy of a water pump installed within the water bath to maintain uniform temperatures within the water. The third objective of this test was to evaluate the option of taping thermocouples to the outside of the specimen molds as opposed to inserting the thermocouples into the soil matrix through holes in the side of the mold.

Due to the excessive rate and depth of frost penetration experienced in preparatory test number four, the voltage in the heat tape was increased to 55 V, and the air temperature within the environmental chamber was increased to 14°F. Twenty thermocouples were used to monitor the temperature profiles of three specimens. Two thermocouples monitored air temperatures, and two more measured water temperatures. One thermocouple was placed in the location with the least amount of water circulation, while another was placed directly in the path of water flow from the pump. The measured temperatures were then compared. During preparatory test 3, a difference of 1.62°F was experienced at different locations within the water bath. After the water pump was installed, the average temperature difference between locations was reduced to 0.13°F.

Six thermocouples were used to compare the temperature inside the soil matrix to the temperature just outside of the plastic specimen mold. Three thermocouples were inserted 1 in. into the soil through holes drilled through the sides of the mold at heights of 5 in., 7 in., and 9 in. from the base of the specimen. The other three thermocouples were taped to the outside of the mold at the same heights, and the measured temperatures were compared. The average temperature difference from the soil matrix to the outside of the specimen mold was 0.77°F. This temperature difference was judged to be significant enough to eliminate the use of thermocouples outside the specimen mold in future testing of fine-grained soils.

The placement of thermocouples within the specimens had the potential to influence the test results. To the extent that the holes for the thermocouples compromised the integrity of the lateral insulation in the region around the hole, the
thermocouple readings may have been adversely affected by the very presence of the thermocouples. This interference was minimized by placing duct tape over the holes and thermocouples. The tape minimized air and water movement between the interior and exterior of the specimen.

After preparatory test 5, frost was noticed between the end of the insulation roll and the specimen. In order to eliminate the cavity created by the square ends of the pads, all rolls of lateral insulation were tapered to points at the ends.

3.4.6 Preparatory Test 6
One objective of preparatory test 6 was to establish the voltage and the air temperature settings that would position the frost front at a height of between 3 in. and 5 in. from the base of the specimen. An additional objective was practicing an actual frost heave test by weighing the specimens before and after the test.

The voltage in the heat tape was maintained at 55 V, but the air temperature within the environmental chamber was raised to 19.4°F to decrease frost penetration in the specimens. The total number of thermocouples used was increased to 26. Three specimens were each instrumented with seven thermocouples arranged to measure the temperatures of the specimen at 1-in. intervals from the soil surface down to a height of 3 in. above the base of the specimen. Three thermocouples measured the water temperature at randomly selected locations, and two thermocouples measured the air temperature. This thermocouple arrangement was later adopted for use in frost heave testing of a Montana silt as described in Chapter 4.

3.4.7 Preparatory Test 7
Two water circulation tests were conducted to verify the efficacy of the water pump. The first test was performed with the pump operating. Dummy specimens were placed in the bath for the water to flow around, the pump was turned on, and the water was allowed to circulate for approximately 5 minutes before the test began. Approximately 0.85 fl. oz. of blue dye was added to the bath water directly in front of the pump. In less than 1 minute and 30 seconds, the dye was entirely diffused throughout the bath, and the water was a uniform blue color.
In the second test, 0.85 fl. oz. of red dye was poured into the full bath with the same dummy specimens as in the first test, but without the use of the pump. Photographs were taken at the beginning of the test and at 3, 6, and 10 minutes as shown in Figure 3.18. After 10 minutes, the dye had still not diffused, so the pump was turned on. Figure 3.19 shows the bath at various times after the pump was turned on. After 2 minutes and 45 seconds of water circulation, no variation in water color was visible.

(a) Time = 0 minutes 0 seconds.  
(b) Time = 3 minutes 0 seconds.  
(c) Time = 6 minutes 0 seconds.  
(d) Time = 10 minutes 0 seconds.  

**FIGURE 3.18 Circulation test with pump off.**
(a) Time = 10 minutes 20 seconds. (b) Time = 10 minutes 50 seconds.

(c) Time = 12 minutes 0 seconds. (d) Time = 12 minutes 45 seconds.

FIGURE 3.19 Circulation test with pump on.

3.5 SUMMARY
The BYU frost heave test apparatus consists of a single bath container that facilitates simultaneous testing of nine specimens. Heated water in the base of the bath supplies both heat and water to all nine specimens. An aluminum frame suspends the heave measurement devices above the specimens, and the entire apparatus is placed in an environmental chamber that cools the specimens collectively.

Several preparatory tests were conducted with the goals of minimizing the difference between laboratory and natural conditions, verifying the functionality of the apparatus, and establishing a testing protocol which could be used in future testing. In order to simulate a natural thermal gradient and to achieve the desired depth of frost penetration, a different combination of temperature and voltage settings were used in each test. In this way, the optimum settings were determined by iteration. Table 3.1 shows the temperature and voltage settings used during preparatory testing. During the
TABLE 3.1 Variac and Temperature Settings and Frost Penetrations

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Variac Setting (V)</th>
<th>Air Temperature (°F)</th>
<th>Frost Penetration (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparatory Test 1</td>
<td>No Variac</td>
<td>23.0</td>
<td>None</td>
</tr>
<tr>
<td>Preparatory Test 2</td>
<td>75</td>
<td>23.0</td>
<td>None</td>
</tr>
<tr>
<td>Preparatory Test 3</td>
<td>45</td>
<td>23.0</td>
<td>None</td>
</tr>
<tr>
<td>Preparatory Test 4</td>
<td>45</td>
<td>10.4</td>
<td>9.0</td>
</tr>
<tr>
<td>Preparatory Test 5</td>
<td>55</td>
<td>14.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Preparatory Test 6</td>
<td>55</td>
<td>19.4</td>
<td>4.6</td>
</tr>
</tbody>
</table>

first preparatory test, no variac was used, and therefore the voltage in the heat tape was approximately 115 V. In preparatory tests 4 and 5, the frost front penetrated the full length of the specimens.

Unfortunately, not all questions were answered during preparatory testing, and some of the desired features were not able to be incorporated into the frost heave device. The first limitation is the absence of an automated method of controlling the frost penetration rate. While the author suggested in Chapter 2 that this would be a desirable feature, the omission of this feature can be mitigated to a large degree by using a system of trial and error, where the temperatures of the specimens are continuously monitored and the settings of the environmental chamber are altered as needed through the duration of the experiment.

The second limitation is that no adaptations have been made to measure the heaving pressures created by the heaving specimens. Future construction of a frame that could surround a specimen being tested and measure the heaving pressures is a possibility, but at the present no such equipment has been developed and tested for the BYU frost heave apparatus.

The third limitation is the lack of external control of the water height during testing. This limitation, however, is viewed as of minor consequence since after a 10-day test the water level was lowered by only 0.19 in. as a result of water uptake by all nine specimens.
With the construction and preparatory testing phases of the frost heave apparatus project completed, the device was then ready to conduct a full-scale testing run. Chapter 4 presents the results of those tests.
CHAPTER 4
FROST HEAVE TESTING OF MONTANA SILT

4.1 VALIDATION OF FROST HEAVE APPARATUS
In order to test the capabilities of all systems and verify the functionality of the frost heave apparatus, a highly frost-susceptible soil was obtained from the Montana Department of Transportation and subjected to a regimen of tests similar to those anticipated for future materials characterizations and frost heave analyses. The purpose of this testing was to evaluate the efficacy of Portland cement treatment for reducing the frost susceptibility of a Montana silt.

The soil has been used as a subgrade and was obtained from a borrow pit near Four Corners, Montana, along U.S. Highway 84 approximately 9 miles west of Bozeman, Montana. Figure 4.1 shows the exact location of the site. The following sections describe the experimental procedures and test results.
FIGURE 4.1 Soil origin.
4.2 PROCEDURES
This section describes the methods of soil characterization utilized in the research, strength and moisture susceptibility testing procedures, and the frost heave testing protocol used to assess the effects of cement stabilization on the frost susceptibility of the Montana silt.

4.2.1 Soil Characterization
The Montana silt was first classified using two principal methods, the Unified soil classification system (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) classification system. These methods are based on particle-size distributions and Atterberg limits, with the AASHTO method being the most common specification used in the United States for highway design.

Soil preparation began with drying at 140°F for 24 hours. After the soil was dried, it was sieved through various sieve sizes to facilitate construction of replicate specimens with identical gradations. A washed sieve analysis was performed according to ASTM D 2217 to determine the particle-size distribution of the soil over nine sieve sizes. A hydrometer test was also conducted according to ASTM D 422 to determine the particle-size distribution of the portion of the sample finer than 0.003 in. (29). Atterberg limits tests were performed according to ASTM D 4318 to determine the plastic and liquid limits of the soil, and the apparent specific gravity of the material was measured following ASTM D 854 (29).

The electrical conductivity of the soil was also assessed to give an indication of the salinity of the soil, which can have a direct impact on frost heave behavior. As described in Chapter 2, both the freezing temperature of the soil water and the magnitude of matric suction that develops upon freezing are dependent on salinity. For this test, 0.011 lb of air-dried soil was placed into a clean bottle with 0.220 lb of deionized water. The soil and water were thoroughly mixed, and a dual platinum-plate, contacting-type probe was used to measure the electrical conductivity of the solution. Measurements were taken at specified intervals until the electrical conductivity stabilized at a constant value.
4.2.2 Soil Compaction and Strength

As the Montana silt tested in this research was a highway subgrade soil, the standard Proctor compaction effort was utilized in specimen preparation. Each specimen was prepared by weighing out exact amounts of each particle size as determined by the dry sieve analysis that had been conducted previously. The optimum moisture content and maximum dry density were determined by compacting multiple specimens at various moisture contents. Data from the optimum moisture content analysis showed that this soil retains a gravimetric moisture content of approximately 2 percent in the air-dry condition. Thus, a correction in the amount of water needed for compaction at the optimum moisture content was applied during specimen preparation.

State highway departments commonly specify unconfined compressive strengths for cement-treated soils used in road construction. In this research, cement contents corresponding to 7-day unconfined compressive strengths of 200 psi, 400 psi, and 600 psi were selected for evaluation; these target values represent the typical range of values specified by highway agencies. The specimens were prepared with various amounts of Portland Type I/II cement and tested for strength according to ASTM D 1633, except that the specimens were not soaked before testing (29). In order to provide water for cement hydration while still maintaining sufficient moisture for compaction, an additional amount of water was added to the specimens that contained cement. The weight of the additional water was equal to 20 percent of the weight of the cement added. All samples were compacted using the standard Proctor compaction effort and allowed to cure for 7 days at 100 percent relative humidity. After curing, the specimens were capped with gypsum and tested in a compression machine at a strain rate of 0.05 in. per minute. A floating head was used to ensure a uniform distribution of load across the specimen end caps. The maximum loads sustained during testing were utilized to compute the unconfined compressive strengths of the specimens, which were in turn employed to determine the target cement contents for use in the research.
4.2.3 Moisture Susceptibility Testing

In addition to strength testing, the moisture susceptibility of the soil was also assessed. Moisture susceptibility testing was performed using the Tube Suction Test (TST) as outlined in Texas Department of Transportation Test Method Tex-144-E. For the TST, three replicate specimens prepared at four different cement treatment levels were compacted in plastic containers pre-drilled with 0.0625-in.-diameter holes in the bottom and allowed to cure at 100 percent relative humidity for 7 days.

After the curing period, the specimens were dried at 140°F for 72 hours. Once the drying process was complete, the specimens were placed in a 0.5-in.-deep bath and allowed to imbibe water over a 10-day soaking period. The surface dielectric values of the specimens were then measured daily during this period, with six readings per specimen taken at each time interval.

The dielectric value of a soil medium is most sensitive to the presence of unbound water, which plays a primary role in numerous pavement damage mechanisms. For materials with high suction and sufficient permeability, substantial amounts of unbound water rise within the aggregate matrix, leading to higher dielectric values at the surface. Non-moisture-susceptible materials, on the other hand, maintain a strong moisture gradient throughout the test, with little moisture reaching the surface, and have lower dielectric values at the end of the TST.

The interpretation of TST results is based on an empirical relationship between the final dielectric value and the expected performance of aggregate base materials (30). Aggregates whose final dielectric values in the TST are less than 10 are expected to provide superior performance, while those with dielectric values above 16 are expected to provide poor performance as base materials. Aggregates having final dielectric values between 10 and 16 are expected to be marginally moisture susceptible. Laboratory tests have confirmed a positive correlation between the TST moisture susceptibility classifications and the strength loss and frost heave characteristics of pavement base materials (31, 32, 33).
4.2.4 Frost Heave Testing

Once the soil characteristics were established and the initial tests were complete, the frost heave tests were performed. This section describes the procedures used to prepare the various components of the apparatus and the specimens for frost heave testing, as well as the protocol followed for temperature settings and data collection.

4.2.4.1 Bath Preparation

Before frost heave testing was conducted, the bath, table, and collars of the apparatus were thoroughly cleaned with distilled water and dried. The caulking of the bath was inspected, and 10 gallons of distilled water was placed in the bath for each test. The height of the water was set between 1.75 in. and 2.0 in. deep.

4.2.4.2 Specimen Preparation

Each frost heave specimen was prepared using proportions representative of the different particle sizes calculated from the dry sieve analysis initially conducted on the material and compacted into cylindrical molds pre-drilled with seven 0.125-in.-diameter holes in the bottom to allow for water uptake. A filter paper was placed in the bottom of the mold prior to compaction in order to prevent the ejection of fines into the bath water during frost heave testing. The weight of the mold and specimen together was measured just after compaction in each case, and four height measurements were taken to determine the initial height of each finished specimen. The specimens were then cured at 100 percent relative humidity for 28 days and weighed again (2).

Seven thermocouples were inserted into three specimens at 1-in. intervals beginning at the soil surface and extending down the sides of the specimens to a height of 3 in. from the specimen base. The thermocouples were inserted to a depth of 1 in. into the specimen on opposing sides of the mold in alternating fashion so that the thermocouples were equally distributed on both sides of the mold. Duct tape was then placed over each thermocouple hole in order to seal the hole, provide support for the thermocouple wire, and minimize the disturbance at the interface between the exterior of the mold and the inner wrap of lateral insulation. An example of a specimen instrumented with thermocouples is shown in Figure 4.2. Before testing began, the
overburden weights were cleaned and oiled to retard the rusting of the weight and to minimize adfreezing between the steel weight and the mold.

4.2.4.3 Insulation Preparation
After the specimens were instrumented, they were wrapped with lateral insulation. In each case, the insulation extended above the top of the mold and downward along the length of the specimen to where the insulation rested on, and entirely covered, the surface of the collar. The lateral insulation was held in place by an elastic band. After the specimen was instrumented and the insulation was in place, the specimens were placed into the bath through the collar and table. The overburden weights were then placed on the specimen surfaces.

4.2.4.4 External Frame Preparation
The LVDTs were arranged according to the numbers etched into the frame at each rod holder. Prior to the start of the test, each LVDT clamping rod was adjusted to allow the full range of motion for each LVDT during the test. After each LVDT assembly was
positioned at the prescribed height, the entire external frame was adjusted horizontally to ensure that the LVDTs were centered on each specimen.

4.2.4.5 Test Randomization and Replication

To ensure statistically sound results, three replicates of four different cement treatment levels were tested. With a total of 12 specimens to be tested, two separate frost heave runs were conducted. Given that the bath capacity is limited to nine specimens, three specimens remained to be tested during the second test run; thus, six locations of the apparatus were filled with dummy specimens compacted using the same Montana silt and the same compaction process. The placement of the samples within the apparatus was randomized as shown in Figure 4.3.

In addition to using identical environmental chamber and variac settings, two measures were taken to verify that the first and second test exposed the prepared specimens to identical conditions. First, three thermocouples were placed in the bath water at various locations to facilitate comparisons of the water temperatures measured in both tests. Second, two additional thermocouples measured air temperatures above the specimens to verify that the air temperatures the specimens experienced during the separate tests were identical.

![Specimen layout during testing](image)

(a) Test run 1. (b) Test run 2.

FIGURE 4.3 Specimen layout during testing.
4.2.4.6 Temperature Settings and Data Collection

Frost heave testing was initiated by setting the environmental chamber temperature to 19.4°F; the temperature of the chamber prior to the start of the test was set at 68°F. The voltage allowed through the heat tape was 55 V. Both the temperature profiles and the changes in specimen lengths were automatically recorded on 10-minute intervals throughout the duration of the 10-day test using a computerized data acquisition system.

Directly after the frost heave test, the excess water was wiped off the specimen, the insulation and instrumentation were removed, and the combined weight of the specimen, mold, and overburden was measured. The overburden weights were not removed because they were still frozen to the specimens. Following the weight measurements, four specimens were removed from their molds before significant thawing could commence, and the frozen specimens were closely examined. The height of the lowest ice lens was recorded together with the lengths of the area with lenses and the area without lenses. The final total length was also measured on the specimens removed from the molds so that comparisons could be made between the the observed lengths and the lengths measured by the LVDTs.

After the ice lensing observations were documented, the specimens were placed in an oven at 230°F. The drying time was anticipated to be between 48 and 72 hours; however, the actual time required to fully dry a specimen was determined to be significantly longer. By weighing the specimens at regular intervals during the drying process, the time required to fully dry a specimen that was still in its mold was found to be 11 days. The time required to dry a sample removed from its mold and placed in a drying pan was 7 days.

4.3 TEST RESULTS

This section presents the results of the soil characterization, strength and moisture susceptibility evaluations, and frost heave tests conducted on the Montana silt utilized in this research. The majority of the section gives a detailed report of the results obtained from frost heave testing.
4.3.1 Soil Characterization

Tests conducted to classify the soil and to determine its physical characteristics included a washed sieve analysis, a hydrometer analysis, Atterberg limit tests, a specific gravity test, and an electrical conductivity test. The Montana silt had liquid and plastic limits of 25.80, and 25.79 percent, respectively, indicating that the soil is non-plastic. The apparent specific gravity of the soil was found to be 2.67. The grain-size distribution is shown in Figure 4.4. As discussed in Chapter 2, certain grain-size distributions are associated with greater frost susceptibility than others. According to this particle-size distribution and the measured Atterberg limits, this soil is classified as an A-4 (0) material in the AASHTO classification method and as ML, which is silt with sand, in the USCS. According to the frost susceptibility classification system developed by the USACE, this soil meets the requirements for an F-4 rating, the most frost-susceptible classification possible.

The electrical conductivity of the soil is an indicator of the amount of salts in the soil, which can affect the formation of ice lenses as discussed in Chapter 2. After 26 days of testing, the electrical conductivity readings stabilized at approximately 432 micro-

![FIGURE 4.4 Soil particle-size distribution.](image)

54
Siemens per in. This comparatively low salt concentration was expected, as the soil was obtained from a borrow pit and had never been exposed to deicing salts.

### 4.3.2 Soil Compaction and Strength

Three additional tests were conducted to investigate the strength and behavior of the material. First, a moisture-density curve was established as shown in Figure 4.5. This curve indicates that the optimum moisture content is 20 percent and the maximum dry density is 101 lb/ft³ when the standard Proctor method of compaction is used.

The unconfined compressive strength test revealed that the desired compressive strengths of 200 psi, 400 psi, and 600 psi were approximately obtained when the soil was mixed with, 2.0, 3.5, and 5.0 percent cement, respectively. Figure 4.6 shows the compressive strengths of the samples tested at various cement contents.

![FIGURE 4.5 Moisture-density curve.](image-url)
4.3.3 Moisture Susceptibility Testing

The TST was conducted in an effort to correlate dielectric measurements to frost susceptibility. The average dielectric values at the end of the TST are shown in Table 4.1 together with the corresponding level of moisture susceptibility. The dielectric values plotted over time are shown in Figure 4.7.

According to the moisture susceptibility ratings resulting from the TST, all specimens have the potential for frost heave; all of the final dielectric values exceed 10. The TST also indicates that increased cement content decreases the moisture susceptibility of the soil.
TABLE 4.1 Tube Suction Test Results

<table>
<thead>
<tr>
<th>Cement Content (%)</th>
<th>Average Final Dielectric Value</th>
<th>Moisture Susceptibility Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>21.9</td>
<td>Poor</td>
</tr>
<tr>
<td>2.0</td>
<td>15.8</td>
<td>Marginal</td>
</tr>
<tr>
<td>3.5</td>
<td>14.2</td>
<td>Marginal</td>
</tr>
<tr>
<td>5.0</td>
<td>11.2</td>
<td>Marginal</td>
</tr>
</tbody>
</table>

FIGURE 4.7 Average dielectric readings.

4.3.4 Results of Frost Heave Tests
Table 4.2 shows data collected from the 12 frost heave samples. The analysis that follows is based mainly on this information and the temperature data that were collected during the test.
### TABLE 4.2 Frost Heave Test Data

<table>
<thead>
<tr>
<th>Cement Content (%)</th>
<th>Moisture Content at Compaction (%)</th>
<th>Dry Density at Compaction (lb/ft³)</th>
<th>Initial Length (in.)</th>
<th>Length Change during Test (in.)</th>
<th>Weight Gain during Test (lb)</th>
<th>Moisture Content at End of Test (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>20.5</td>
<td>106.7</td>
<td>8.57</td>
<td>1.18</td>
<td>1.02</td>
<td>30.0</td>
</tr>
<tr>
<td>0.0</td>
<td>19.8</td>
<td>106.8</td>
<td>8.65</td>
<td>1.17</td>
<td>1.02</td>
<td>29.5</td>
</tr>
<tr>
<td>0.0</td>
<td>20.2</td>
<td>106.9</td>
<td>8.57</td>
<td>1.21</td>
<td>1.25</td>
<td>29.8</td>
</tr>
<tr>
<td>2.0</td>
<td>19.8</td>
<td>101.3</td>
<td>9.27</td>
<td>1.50</td>
<td>1.45</td>
<td>34.6</td>
</tr>
<tr>
<td>2.0</td>
<td>19.8</td>
<td>101.8</td>
<td>9.22</td>
<td>1.25</td>
<td>1.77</td>
<td>33.0</td>
</tr>
<tr>
<td>2.0</td>
<td>20.1</td>
<td>101.5</td>
<td>8.96</td>
<td>1.34</td>
<td>1.62</td>
<td>34.0</td>
</tr>
<tr>
<td>3.5</td>
<td>19.0</td>
<td>100.6</td>
<td>9.32</td>
<td>-0.04</td>
<td>0.92</td>
<td>25.9</td>
</tr>
<tr>
<td>3.5</td>
<td>19.4</td>
<td>99.8</td>
<td>9.59</td>
<td>0.06</td>
<td>1.11</td>
<td>27.1</td>
</tr>
<tr>
<td>3.5</td>
<td>18.9</td>
<td>100.5</td>
<td>9.30</td>
<td>-0.04</td>
<td>0.66</td>
<td>25.8</td>
</tr>
<tr>
<td>5.0</td>
<td>19.1</td>
<td>100.6</td>
<td>9.04</td>
<td>-0.04</td>
<td>0.78</td>
<td>25.4</td>
</tr>
<tr>
<td>5.0</td>
<td>17.9</td>
<td>100.2</td>
<td>9.38</td>
<td>-0.03</td>
<td>1.04</td>
<td>25.2</td>
</tr>
<tr>
<td>5.0</td>
<td>19.1</td>
<td>100.3</td>
<td>9.08</td>
<td>-0.03</td>
<td>0.60</td>
<td>25.8</td>
</tr>
</tbody>
</table>

Figures 4.8 and 4.9 show relationships between the cement content, water uptake, and frost heave exhibited by the tested specimens. The bar in the figures represents the average value, while the upper and lower ends of the lines denote the high and low data points, respectively.

![Figure 4.8](image.png)

**FIGURE 4.8** Frost heave at end of 10-day test.
Treatment of the silty Montana subgrade soil with cement proved to be effective in controlling frost heave when a sufficient amount of cement was added; however, when an insufficient amount of cement was applied, the frost heave exhibited was actually greater than that observed in untreated samples. This behavior is likely caused by an increase in matric suction, but an insufficient reduction in permeability, associated with the addition of 2 percent cement. Furthermore, treatment with just 2 percent cement apparently did not permit development of the strength necessary to resist the heaving pressures that occurred in this material during freezing. The data collected for specimens treated with 3.5 percent and 5.0 percent cement suggest that once a sufficient amount of cement required to prevent frost heave is reached, the addition of more cement only marginally increases resistance to frost heave. The slight decrease in length exhibited by the specimens with 3.5 percent and 5.0 percent cement was likely caused by thermal contraction as the specimens cooled.

The specimens with 5.0 percent cement imbibed 73 percent as much water as did the untreated control specimens and exhibited negative frost heave, whereas the control group heaved an average of 1.19 in. This result shows that although the cement treatment
is totally effective in eliminating frost heave, it is only marginally able to reduce water flow into the soil. This observation is consistent with the marginal moisture susceptibility rating received by these specimens in the TST.

Temperatures were measured throughout the duration of the tests using thermocouples as described previously. Figure 4.10 shows the typical temperature profile of a specimen throughout the duration of the test. The coldest temperature occurs at the surface and increases at a constant rate with increasing specimen depth. As previously mentioned, the temperature gradient across the frozen fringe in a typical soil column under a roadway is 0.27°F/in. (20). Based on that estimation, the theoretical difference in temperature between the top and bottom of a 9-in.-tall specimen should be 2.43°F. While testing the Montana silt, however, the actual temperature difference between the top and bottom of the specimens was 10.80°F, which corresponds to a thermal gradient of 1.20°F/in.

Air and water temperatures were also monitored throughout the test. Thermal equilibrium was reached at a time of approximately 100 hours from the beginning of the frost heave test. Analysis of the water temperatures after 100 hours showed the mean

![Graph showing temperature readings at various heights within a specimen.](image)

**FIGURE 4.10 Temperature readings at various heights within a specimen.**
water temperature to be 36.50 ± 0.10°F and the air temperature to be 19.09 ± 1.18°F. Figures 4.10 and 4.11 suggest that the minor fluctuations of the air temperature had no visible impact on the temperatures of the specimens or the water, however.

The data collected by the LVDTs also provided valuable information about the frost heave characteristics of the soil. Figure 4.12 shows a graph of the axial elongation of four specimens representative of each cement treatment level.

![Graph of axial elongation](image)

**FIGURE 4.11 Typical temperatures for air and water during testing.**
Although thermal equilibrium was reached at approximately 100 hours into the test, a constant frost heave rate was not reached until approximately 134 hours into the test. From this time forward, the heave rate remained approximately constant throughout the remainder of the test. Therefore, the time period between 134 and 240 hours, which was the end of the test, was chosen as the basis for calculating the average frost heave rate. Table 4.3 shows both the total amount of heave and the average heave rates experienced by the specimens as a function of cement content.

During the course of the testing, a problem with thermocouple tear-out was observed. As soil below each thermocouple heaved, it pushed the thermocouple upward. The thermocouple was then caught between the frozen soil pushing upwards and the stationary hole in the mold through which it was inserted. This shearing action caused considerable damage to a thermocouple and caused local disruption of the heaving of the specimen. In the future, specimen molds should have slots cut into the sides to allow for the movement of the thermocouples. Cutting slots into the mold and placing the thermocouples at the bottoms of the slots will enable the thermocouples to lift with the heave. This concept is shown visually in Figure 4.13.
TABLE 4.3 Total Heave and Heave Rate

<table>
<thead>
<tr>
<th>Cement Content (%)</th>
<th>Frost Heave (in.)</th>
<th>Heave Rate (in./day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>0.0</td>
<td>1.19</td>
<td>0.02</td>
</tr>
<tr>
<td>2.0</td>
<td>1.36</td>
<td>0.13</td>
</tr>
<tr>
<td>3.5</td>
<td>-0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>5.0</td>
<td>-0.03</td>
<td>0.01</td>
</tr>
</tbody>
</table>

FIGURE 4.13 Schematic of a slotted specimen mold.

4.3.5 Point of Heave Initiation

As displayed in Figure 4.10, a sudden rise in temperature occurred in all specimens typically between 36.5 and 48.5 hours into the test. The sudden rise in temperature preceded the start of heaving in all cases by an average of 38 minutes for the specimens that exhibited heave. Although all specimens experienced the increase in temperature, only the untreated specimens and those treated with 2.0 percent cement heaved. At the point of heave initiation, the heave rate increased within a 10-minute period from a negative heave to the highest rate experienced by the specimen.
The point of heave initiation can be explained in the following way. Ice lensing cannot occur exactly at the freezing front in most soil media due to a depression in the freezing temperature of the soil water associated with salinity and matric suction effects (27). Thus, a frozen fringe is established between the lowest ice lens and the freezing front below it. Once the freezing front has penetrated sufficiently into the soil, the pore water near the surface will change to ice. The sudden lack of liquid water near the soil surface dramatically increases the matric suction of the specimen in the vicinity of the ice. In response, pore water originally located lower in the specimen or in the water bath rises into the specimen through capillary rise, which causes the temperature of the soil near the point of water arrival to increase; the increase was measured to be 2.9°F on average in the testing conducted in this research. This warming is due to the energy contained in the water arriving from lower, unfrozen soil. Only after the arrival of this wave of water does ice lensing begin to occur. The initial heave rate then slows to a constant, sustainable rate as the liquid water from the initial wave and the existing pore water are depleted and the rate of water migration to the growing ice lens from lower in the soil specimen reaches a steady state.

Figure 4.14 shows the typical changes in length through time experienced by samples with 3.5 and 5.0 percent cement. The sudden change in length directly relates to the temperatures of the specimens. The increases in length at 40 and 49 hours directly coincide with the point of heave initiation and the sudden rise in temperature that accompanies the arrival of warmer water throughout the specimens.
FIGURE 4.14 Height changes for non-frost-susceptible specimens.

4.4 SUMMARY

Once a frost heave testing protocol was established, a Montana silt was obtained and tested to demonstrate the functionality of the BYU frost heave apparatus. The focus of the testing was to evaluate the effects of cement treatment on the frost heave behavior of the silt. An outline of the tests performed on the material and the motivations for conducting those tests are given in this chapter.

The results of the frost heave tests indicate that cement can be a very effective treatment for reducing frost heave and potentially minimizing frost-associated damage to road structures. However, a sufficient amount of cement must be added to problematic soils to achieve acceptable levels of stabilization. As documented in this research, treatment of frost-susceptible soils with inadequate cement can actually increase frost susceptibility. The collected data also suggest that, although excessive amounts of cement will reduce frost susceptibility, a threshold cement content exists, beyond which additional cement only slightly improves the resistance of the treated soil to frost heave.
CHAPTER 5
CONCLUSION

5.1 SUMMARY
Research in the area of frost heave has been pursued for more than 75 years. During this time, the effectiveness of the testing equipment and the methods used to remediate the effects of frost heave have improved dramatically. However, no system has yet been developed to accurately predict frost heave from standard geotechnical tests. In addition, the need for a versatile and comprehensive frost heave apparatus persists. For these reasons, the BYU Civil and Environmental Engineering Department initiated a project in which a state-of-the-art frost heave apparatus was designed, constructed, and validated.

The apparatus includes six main parts. First is a water bath that provides a communal water and heat source capable of providing water table heights up to 18 in. Second is the external frame that supports the LVDTs used to measure frost heave during the testing. Third is the table and collar assembly that supports the specimens and ensures proper horizontal placement of the specimens in the bath. Fourth are the specimens and the specimen molds, which provide a convenient method to contain and transport the soil being tested. Fifth is the environmental chamber that provides a communal heat sink and that can be used to control the thermal gradient. Sixth is the data collection system that electronically records the temperatures of the air, water, and specimens and also records the axial elongation of the specimens.

After construction of the frost heave test apparatus was complete, a series of preparatory tests were conducted to verify the functionality of the device. These tests addressed such issues as thermal gradient control, uniformity of water temperature, adequacy of lateral insulation, thermocouple placement, and data acquisition. After the full set of preparatory tests was complete, a full-scale frost heave test was conducted as a means of validating the functionality of the frost heave testing apparatus. The frost heave
test was used to evaluate the effectiveness of cement treatment for preventing frost-associated damage to a Montana silt.

Based on the USCS and the AASHTO soil classification, the soil was classified as an F-4 material according to the USACE frost classification system. Tests to determine the optimum moisture content and specific gravity of the material were also performed. Unconfined compressive strength tests were performed at various cement contents to determine the levels of cement needed to produce unconfined compressive strengths of 200 psi, 400 psi, and 600 psi; the resulting cement contents were 2.0, 3.5, and 5.0 percent. Three replicate specimens treated at each of these cement levels, as well as three untreated specimens, were then subjected to moisture susceptibility tests and frost heave tests. Specimens were prepared using the standard Proctor compaction effort.

5.2 FINDINGS
During the course of this research, much information concerning the simulation of frost heave and the freezing behavior of cement-treated silt was gained as discussed in the following sections.

5.2.1 Desirable Features of Frost Heave Devices
The overall strength of a frost heave testing apparatus can be measured by an evaluation of its compliance with the 12 target objectives listed in Chapter 2. For clarity, the 12 main objectives have been categorized into two general groups in Table 5.1. The first main concept concerns accuracy of the simulation, and the second concept concerns the use of technology.

<table>
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<th>TABLE 5.1 Apparatus Objectives</th>
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<tr>
<td><strong>Accuracy of Simulation</strong></td>
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<tr>
<td>Control of Thermal Gradient</td>
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<td>Rate of Frost penetration</td>
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<tr>
<td>Specimen Size Capacity</td>
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<td>Control of Lateral Expansion</td>
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<tr>
<td>Variability of Water Supply</td>
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<tr>
<td>Simulation of Overburden</td>
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<tr>
<td>Minimization of Adfreezing</td>
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The BYU frost heave apparatus satisfies all of the objectives listed in Table 5.1 except for the ability to measure heaving pressures and automatically control the rate of frost penetration. However, the rate of frost penetration can be externally controlled by closely monitoring the chamber air temperature and the temperature profiles of the specimens, and the addition of a component to measure heaving pressures can be easily accommodated within the existing device.

5.2.2 Effects of Cement Treatment on a Montana Silt

The results showed that frost heave actually increased with the addition of 2.0 percent cement compared to the control group, while cement treatments of 3.5 percent and 5.0 percent cement produces negative values of frost heave. Water uptake also followed the same trend, with the specimens treated with 2.0 percent cement imbibing an average of 0.51 lb of water more than the control group and 0.72 lb and 0.81 lb more than the 3.5 percent and 5.0 percent groups, respectively.

The behavior of the soil at the point of heave initiation was well documented. The Montana silt utilized in the research displayed thermal contraction for the first 33 hours of the frost heave test. Between 33 and 50 hours, the initiation of heave was distinctly observed for all specimens and was accompanied by an increase in temperature throughout the specimen, with the largest increase in temperature occurring at the surface of the specimen and decreasing linearly down through the specimen. This increase in temperature is assumed to be caused by the arrival of warmer water drawn up by the sudden increase in matric suction caused by the formation of ice near the soil surface.

5.3 RECOMMENDATIONS

This research resulted in several recommendations relating to frost heave testing and treatment of soil and aggregate materials to minimize the occurrence of frost heave.

5.3.1 Recommendations for Improvements to the Frost Heave Apparatus

In an effort to both minimize the effects of adfreezing and to minimize the lateral expansion of a specimen as it freezes, a mold constructed of a sturdy yet non-thermally-

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conductive material would be desirable. This mold would have the water uptake holes drilled into it on the bottom and would have slots drilled into it on the sides in order to allow the thermocouples to move with the specimen as it heaves.

Two additional instruments would give valuable insight to the process of frost heave and make the apparatus a more valuable research tool. The first would be to place an electronic scale on the top of a platform above the external frame. The specimen would then be suspended from the scale and hang so that the bottom of the specimen would be located approximately 0.25 in. above the bottom of the bath during the test. This setup would allow continuous weight measurements to be taken throughout the test. The second suggested improvement to the apparatus would be a frame that could be placed around a specimen to restrict upward heave and allow measurement of the heaving pressure exerted by the specimen as it freezes.

Regarding test procedures, the foremost recommendation is for further experimentation to be performed with various combinations of warmer freezing temperatures and colder bath water temperatures. Such temperature conditions would decrease the thermal gradient across tested specimens and enhance the overall simulation of natural freezing conditions in the frost heave apparatus. However, the cold temperature should not be increased above 26.6°F, and the water temperature should not be decreased below 33.8°F. This maximum cold temperature still easily accommodates ice nucleation, and the minimum warm temperature prevents freezing of the bath water below the table. Use of an electronic thermostat in the bath itself to automatically control the bath water temperature should also be considered.

5.3.2 Recommendations for Cement Treatment and Future Testing

The value of adding a sufficient amount of cement to the Montana silt evaluated in this research has been established; however, the effects of cement treatment on a variety of different soil types must be analyzed before any general guidelines can be offered with regards to soil stabilization in general. A cyclic freeze-thaw test is recommended to evaluate the long-term performance of cement-treated road bases as well. This cyclic test should also include a measurement of the thaw-weakening potential of the soil, perhaps by the California bearing ratio test.
REFERENCES


