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Development and Demonstration of an Apparatus for Assessing Frost-Heave Susceptibility of Soil

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DEVELOPMENT AND DEMONSTRATION OF AN APPARATUS FOR ASSESSING FROST-HEAVE SUSCEPTIBILITY OF SOIL

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ABSTRACT

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The objective of this research was to develop and demonstrate an apparatus for assessing the frost-heave susceptibility of soil in a laboratory setting. Development of the frost-heave testing apparatus required several components, including a freezing system, a heating system, temperature controllers, a metal frame, a water delivery system, and an insulated specimen container. For the freezing system, a chest freezer was selected to provide a test environment that can be maintained at an adjustable air temperature below 32 °F. For the heating system, thermostat-controlled heat tape was selected for positioning around the base of the specimen and along the water line inside the freezer. For temperature controllers, relays with integrated temperature sensors were selected and connected to the chest freezer and heat tape. For two trial 10-day frost-heave tests of clayey soil and silty soil, graphs were developed to show the change in specimen height over time and to show the actual water and air temperatures, as compared to the target temperatures. As expected, the silty soil heaved more than the clayey soil. The apparatus was able to achieve the target temperatures to within 2.2 °F.

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INTRODUCTION

Frost heave of soil can impact road and building conditions in cold climates by cracking and breaking up pavements and foundations. In cold climates, such as those typical of the northern United States and Canada, frost heave is a phenomenon that requires special consideration for civil infrastructure (Konrad, 1988; Meyer et al., 2023; Taber, 1930). Frost heave, which results from the expansion of freezing soil, can begin at the start of winter and continue until thawing occurs during spring. Once the frozen soil has thawed, high water contents can lead to thaw-weakened soil that may cause further deterioration of affected infrastructure.

Frost heave of susceptible soil occurs as heat flows from the soil into the freezing air, causing the formation of ice within the soil. The initial freezing of the soil can happen quickly and is responsible for relatively small amounts of frost heave as water increases in volume while changing from a liquid state to a solid state (Taber, 1930). However, the more interesting and complicated part of frost heave happens over time in the presence of sustained freezing temperatures. As the freezing front, or 32 °F isotherm, proceeds into the ground, the development of cryosuction in the soil leads to the movement of additional liquid water from underlying soil strata toward the freezing front (Gilpin, 1980; Taber, 1930). Cryosuction occurs as water in the pore spaces, or capillaries, within the soil begins to freeze, which reduces the average diameter of the capillaries and thereby increases the height of capillary rise. As the incoming water freezes and expands, ice lenses can form within the soil. Ice lenses are layers of ice integrated into the frozen soil, and they can cause significant additional frost heave. For this reason, assessing the frost-heave susceptibility of soils prior to the construction of civil infrastructure in cold regions is critical.

The objective of this research was to develop and demonstrate an apparatus for assessing the frost-heave susceptibility of soil in a laboratory setting. A literature review on the general topic of frost heave is first presented. Then, the method for developing the frost-heave testing apparatus is discussed in detail, with images chronologically detailing the process. Following the methodology, results from trial frost heave tests are presented and discussed. Finally, a conclusion summarizes the important contributions of this work.

LITERATURE REVIEW

Based on a literature review performed for this research, the following sections give the motivation for frost-heave studies, explain the mechanics of frost heave, and describe existing frost-heave testing apparatuses.

Motivation for Frost-Heave Studies

Although the mechanics of frost heave have been studied in detail over the last 100 years, frost-heave testing has not been standardized, and a testing apparatus is not commercially available. Therefore, further research into the mechanics of frost heave is important, especially in the field of pavement and materials engineering, to develop standardized testing and improve roadway performance in cold regions. Specifically, frost heave impacts roadway performance in cold regions as it can cause cracking during winter and reduced bearing capacity during spring when the ice lenses thaw (Konrad, 1988; Rogers, 2013). Research on the mechanics of frost heave has yielded some options for mitigation, such as adding geofoam and/or geosynthetic layers into the subbase materials (McCartney & Zornberg, 2010; Moussa et al., 2019). Further, research on the impact of aggregate base material properties on frost heave in pavements has been conducted (Rogers, 2013). In many of these studies, additional research on aspects of frost heave was recommended; because frost heave continues to adversely impact roadway performance in cold regions each year, a greater understanding of its mechanics and testability is important.

The lack of commercially available testing apparatuses requires that researchers construct their own testing devices. As constraints exist in the laboratory, results from testing can be applied to field projects only to the extent that field conditions can be simulated in the laboratory (Cheng et al., 2022a; Lay, 2005). Simulation of field conditions requires a complex testing apparatus to control specific variables that influence the occurrence of frost heave. The lack of commercially available testing apparatuses further limits the capability of researchers to investigate frost-heave mechanisms or develop standard frost-heave testing procedures. In summary, further frost heave research is important to cold regions engineering due to its applicability, demonstrated through previous research, and lack of standardization and testing options in the field of pavement and materials engineering.

Mechanics of Frost Heave

Initial research into the mechanics of frost heave dates back nearly 100 years to Taber's (1930) discovery that frost heave is caused not only by the 9% increase in volume of water as it freezes in situ, but also, and more importantly, to the movement of water and formation of ice lenses between the soil particles, pushing the soil upward as they grow. With this discovery, research on frost heave accelerated, leading to the identification of fundamental principles during the next several decades.

From this research, three requirements for the occurrence of frost heave were identified as 1) sustained freezing temperatures, 2) an available water source, and 3) a frost-susceptible soil, typically comprising silt (Henry, 2000; Rogers, 2013). When these requirements are met, the potential for frost heave exists, with the magnitude of frost heave depending on the duration of freezing temperatures, the rate at which water can move into the freezing soil, and the overburden pressure associated with any surface load on the soil (Beskow, 1948; Taber, 1930). Konrad and Morgenstern (1980) explained that a constant temperature below freezing at the top of the soil causes heat flow out of the soil and subsequent growth of ice lenses in the direction of heat removal. Hermansson and Guthrie (2005) investigated the sensitivity of frost heave to the availability of subsurface water by testing soil samples in open and closed systems, or with and without a water supply; they found that the availability of water at the base of the sample increased the heaving rate by 32.5% for the tested soil. Han and Goodings (2006) evaluated the impact of soil type on frost heave by conducting tests on clay-like samples. The test results indicated that clay behaves very differently than silt, as the low permeability of clay causes it to behave more like a closed system (Han & Goodings, 2006). These and other studies have explored the effects of the three noted requirements for frost heave and led to greater knowledge of frost-heave mechanics, which is necessary for informing the development of a frost-heave testing apparatus.

The temperature gradient that develops in a freezing soil is a key factor in the development of frost heave (Taber, 1930), and Konrad and Morgenstern (1980) explain that the temperature gradient and the water uptake rate are proportional. Rogers (2013) further explains that temperature gradients and specifically water vapor movement are also correlated. A temperature gradient causes the hydraulic properties of a soil to change with depth as freezing progresses, allowing for the development of frost heave (Zhang et al., 2021).

At the freezing front, which is the depth of the 32 °F isotherm in the soil, the removal of heat from the soil causes in situ water to begin a phase change from a liquid state to a solid state. When the rate of heat removal is matched by the rate of incoming heat from lower soil layers, thermodynamic equilibrium is achieved, and the freezing front is static. At this depth in the soil, ice lenses begin to grow, with incoming water being the primary vehicle for heat transfer (Hoekstra & Miller, 1967; Konrad & Morgenstern, 1980; Loch, 1978; Miller et al., 1975). Thermodynamic equilibrium at the freezing front also means that the effective stress of the soil, or the stress between the soil particles, must be zero at that depth, as the soil particles are separated by ice (Henry, 2000). Therefore, an increase in the overburden pressure, which in turn causes an increase in the effective stress of the soil, causes a decrease in the rate of frost heave in a soil (Beskow, 1948). Ice lenses will continue to grow in the soil until the water source is depleted or the rate of heat removal exceeds the rate of heat replenishment, causing the freezing front to further descend. For these reasons, a water source and the ability of the soil to convey water upward through capillary rise are necessary components of frost heave. If the height of capillary rise is less than the distance between the freezing front and the water source, sustained frost heave will not occur (Beskow, 1948; Hermansson & Guthrie, 2005).

Because most soils contain soluble salts, the effects of salts on the mechanics of frost heave warrant consideration. Salts are interesting to study in relation to frost heave because ice forms in a pure state, meaning that, as the water between soil particles freezes, the salt is excluded into supercooled water films that provide for capillary rise through soil even in the presence of ice (Guthrie & Zhan, 2002). As more water is frozen, the freezing point of the remaining liquid water is further depressed, requiring additional heat removal to freeze additional water. Other research into the impact of salt on the mechanics of frost heave led to the discovery that the direction of water flow impacts how salts are dispersed in the soil and therefore how the soil will heave (Zhang et al., 2021).

In summary, research into the mechanics of frost heave during the last century has established a theoretical framework for explaining the movement of water in response to freezing temperatures, subsequent frost heave of frost-susceptible soil, and the effects of salts, for example, which lower the freezing point of water and allow capillary rise even in the presence of ice. In addition, experimental work on these topics has led to the development of theoretical models that can be used for design and analysis (Cheng et al., 2022b; Guthrie & Zhan, 2002; Liu et al., 2019).

Existing Frost-Heave Testing Apparatuses

During the past 20 years, frost-heave research has included development and evaluation of frost-heave test apparatuses, which are necessarily based on the general understanding of the mechanics of frost heave. To simulate the conditions that lead to frost heave, an apparatus must have an enclosed space where the temperature gradient can be controlled, a water source, a means of measuring the change in height of the tested soil, and in some cases surface weights to simulate overburden pressure (Cheng et al., 2022a). The success of a frost-heave testing apparatus depends on the ability to accurately simulate the thermal gradient, control lateral expansion, minimize adfreezing of the soil to the container in which it is tested, simulate an overburden as applicable, control the water supply or water table height, provide for testing of representative specimen sizes, and control the rate of frost penetration (Lay, 2005). Other factors may include automated data acquisition for continuous monitoring of frost heave and temperatures and considerations related to the durability of the apparatus and the ability to test multiple specimens (Darrow et al., 2008; Konrad, 1988; Lay, 2005). Finally, some apparatuses have been developed to track the path of water during frost-heave testing using a dyed water source (Han and Goodings, 2006).

Reflecting variability in research objectives, different frost-heave testing devices have been prepared with various features; four are considered in detail. One of the first frost-heave testing devices was prepared by the United States Army Corps of Engineers (USACE). The device consists of a clear cylindrical container to allow for observation of the ice lenses, a gravity-fed water supply, and two linear scales that visually demonstrate the frost heave; one scale is stationary and connected to the cylinder, and the other scale is free to move with the soil (AlaskaDOTPF, 2014). The USACE testing device was designed to conduct frost-heave tests lasting several weeks with a slow freeze rate of 0.25

in./day, and photographs could be taken throughout the testing to show the development of ice lenses in the soil (AlaskaDOTPF, 2014).

A second frost-heave testing device was developed by Lay (2005) at Brigham Young University that, notably, allows for the simultaneous testing of 25 specimens. Other unique features of Lay's device include a water bath that provides heat to the bottom of the specimens and up to an 18-in. water table height, an external frame that holds linear variable displacement transducers (LVDTs) to measure heaving of each specimen during testing, and a data collection system that electronically records the water, air, and specimen temperatures and the magnitude of specimen heaving (Lay, 2005).

A third frost-heave testing device was developed by Nurmikolu (2005) that uniquely counteracts the impact of adfreezing on frost-heave results by compacting and testing soil specimens in containers comprising stacks of rubber rings that can separate to accommodate specimen heaving. The testing device also includes a water bath that provides water and a heat source to the bottom of the samples, thermocouples placed in the samples at approximately 1-in. vertical spacing to capture the thermal gradient within the soil, a cooling agent to induce freezing, and LVDTs to measure heave readings that are recorded every 5 minutes with temperature readings (Nurmikolu, 2005). Nurmikolu's device can test up to four specimens at once.

A fourth frost-heave testing device was developed by Darrow et al. (2008) that uniquely measures water intake using a differential pressure transducer. This testing device also includes a cooling source consisting of 50% water and 50% ethylene glycol solution supplied to the top of the specimen, light bulbs acting as a heat source, a sample mold that allows for visual observations during testing, and temperature control to within 1.1°F (Darrow et al., 2008).

The frost-heave testing apparatus developed in this study is similar in many respects to previous apparatuses as it provides a water supply and heat source at the bottom of the specimen, freezing conditions at the top of the specimen, and a displacement sensor to measure heave. It is unique, however, in that it can be constructed and operated without extensive computer programming, without repeated sensor calibrations, and without maintenance of a complex heating or cooling system while providing control over both the water table height and the temperature gradient during testing.

METHODOLOGY

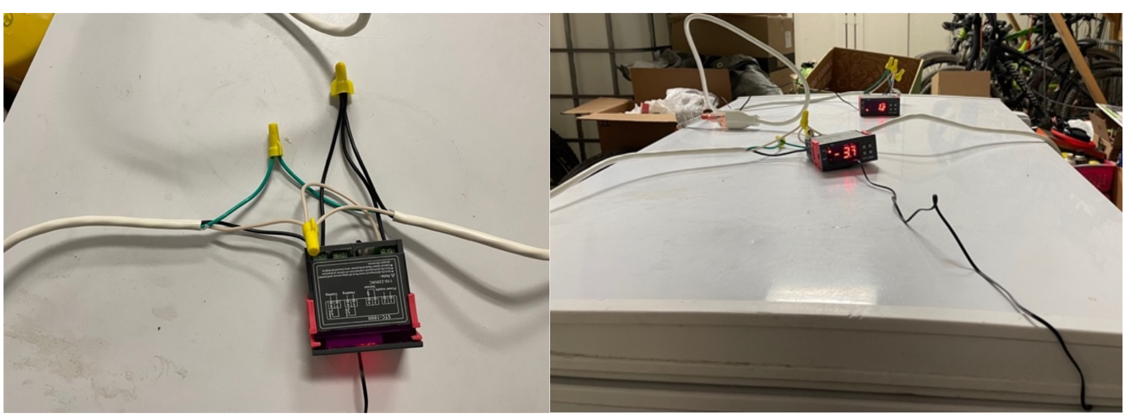
In this section, the process of developing the frost-heave testing apparatus and the procedures associated with initial testing are presented. The process of development of the frost-heave testing apparatus is described chronologically, with images of the apparatus to illustrate the work, and descriptions of the procedures associated with two trial tests are provided.

Development of the frost-heave testing apparatus required several components, including a freezing system, a heating system, temperature controllers, a metal frame, a water delivery system, and an insulated specimen container. For the freezing system, a chest freezer was selected to provide a test environment that can be maintained at an adjustable air temperature below 32 °F. For the heating system, thermostat-controlled heat tape was selected for positioning around the base of the specimen and along the water line inside the freezer. For temperature controllers, relays with integrated temperature sensors were selected and connected to the chest freezer and heat tape; independently controlling the air temperature inside the freezer and the water temperature at the base of the specimen enabled control of the temperature gradient across the length of the specimen. Controlling the temperature gradient is important for simulating winter conditions in the field. If the soil freezes quickly, minimal frost heave can be caused by the 9% increase in the volume of in-situ water as it changes from a liquid state to a solid state; however, slow freezing of a frost-susceptible soil can lead to sustained heaving.

Therefore, as a first step in apparatus development, the temperature controllers were connected to the chest freezer and the heat tape to provide a temperature gradient conducive of frost heave. Figure 1 shows the chest freezer and the temperature controllers. The temperature controller that is connected to the freezer turns power on when the freezer temperature is greater than a specified value and turns power off when it is less than a specified value. The temperature controller connected to the heat tape

Figure 1

Temperature Controllers: (a) Top View and (b) Side View



(a) (b)

turns power on when the water temperature is less than a specified value and turns power off when it is greater than a specified value. The exact air and water temperatures resulting from the temperature controller settings varied as the freezer and heat tape cycled on and off; to document these temperatures, both the air and water temperatures were recorded during the trial tests.

The next steps in developing the frost-heave testing apparatus included designing and building a metal frame that could hold up to two specimens and displacement sensors. Lengths of aluminum angle and square tube were acquired and cut to the design measurements, informed by the interior dimensions of the freezer, before being assembled. Aluminum was chosen as the material for the metal frame because it is a non-corrosive metal that would perform well when exposed to water. The frame includes lower rails to hold the specimens a minimum of 2 in. from the bottom of the freezer for placement of lower insulation and an upper rail across the top of the frame with brackets for the displacement sensors. The rail is set to accommodate specimens with a height of 12 in.; however, the rail may be adjusted to test specimens of different heights in the future. Figure 2 shows the metal frame during assembly.

After the metal frame was complete, the water delivery system was developed. Shown in Figure 3, it includes a Marriott bottle configuration, which allows an adjustable water table height, and a small flexible tube that transfers the water from the bottle to the base of the specimen. In the freezer, a portion of the heat tape is routed along the tube and enclosed inside pipe insulation to prevent freezing of the water. The water table height is controlled using the Marriott bottle by sliding a rigid stainless-steel tube vertically through the rubber stopper that otherwise seals the bottle; the lower end of the tube is

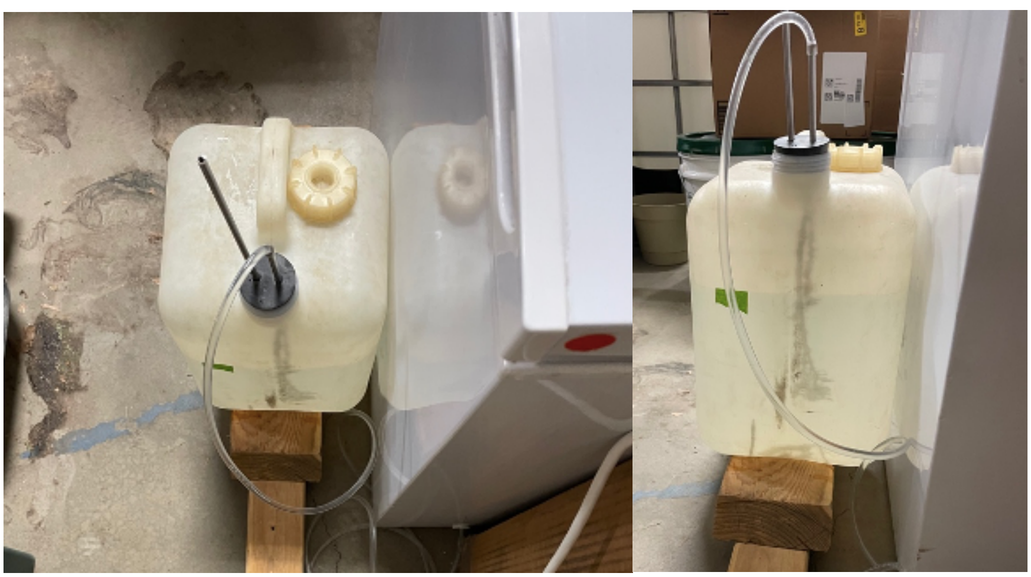
Figure 2

Metal Frame for Specimens and Displacement Sensor: (a) Top View and (b) Side View

(a) (b)

Figure 3

Water Delivery System: (a) Top View and (b) Side View



(a) (b)

placed at an elevation that corresponds to the desired water table height in the specimen. Prior to the trial tests, the water line was primed by tipping the bottle until water flowed out the end of the water line and no air bubbles were visibly trapped in the tube, and then the tube was immediately connected to the base of the specimen.

The next step was to prepare an insulated specimen container, which was constructed of 4.0-in.-diameter polyvinyl chloride (PVC) pipe cut to a length of 13.5 in., a rubber pipe cap, a threaded 0.125-in.-diameter pipe fitting to conduct water from the supply line into the base of the specimen, and foam insulation. A 13.5-in. length was selected for this study because it allows for a 12.0-in. specimen height with additional vertical space to accommodate possible heaving of specimens while properly fitting within the metal frame. The pipe fitting was inserted through a hole drilled into the side of the rubber pipe cap, and a nut placed on the inside of the cap was tightened to ensure that it would not leak water. The rubber pipe cap was then fastened using a hose clamp to the PVC pipe as shown in Figure 4. To insulate the specimen in the radial direction, a closed-cell foam wrap was used. At the bottom of the specimen, beneath the lower rails of the metal frame, a Styrofoam block was cut and placed to prevent heat loss through the bottom of the specimen. The insulation arrangement is depicted in Figure 5.

Following construction of the specimen mold, soil was collected for testing. For the first test, a sample of clayey soil was collected at its natural moisture content from a site in Provo, Utah, and then compacted using the standard Proctor method. Adapted for this research, this method involved compaction of the soil in six lifts, with 32 blows per lift for a total of 192 blows, to achieve a 12-in. specimen height. Prior to testing, this specimen was sealed and stored for 3 days to enable moisture equilibration. For the

Figure 4

Specimen Container: (a) Rubber Pipe Cap with Fitting and (b) PVC Pipe with Cap

(a) (b)

Figure 5

Insulation Arrangement

second test, a sample of silty soil previously collected from a gravel pit in Spanish Fork, Utah, was used. As the soil was completely dry, it was moistened to an 8.2% water content that was estimated to be near the optimum moisture content and compacted in six lifts with 16 blows each, or half of the compaction energy associated with the standard Proctor method, to a height of 12 in. This specimen was tested immediately after compaction. Prior to compaction of both soils, the inside of the container was sprayed with canola oil to minimize adfreezing of the soil to the container during frost-heave testing. An image of the compacted specimen prepared for the first test is shown in Figure 6.

The last steps of the trial frost-heave tests included placement of the specimen in the chest freezer and connecting both the temperature and displacement sensors to the

Figure 6

Compacted Specimen

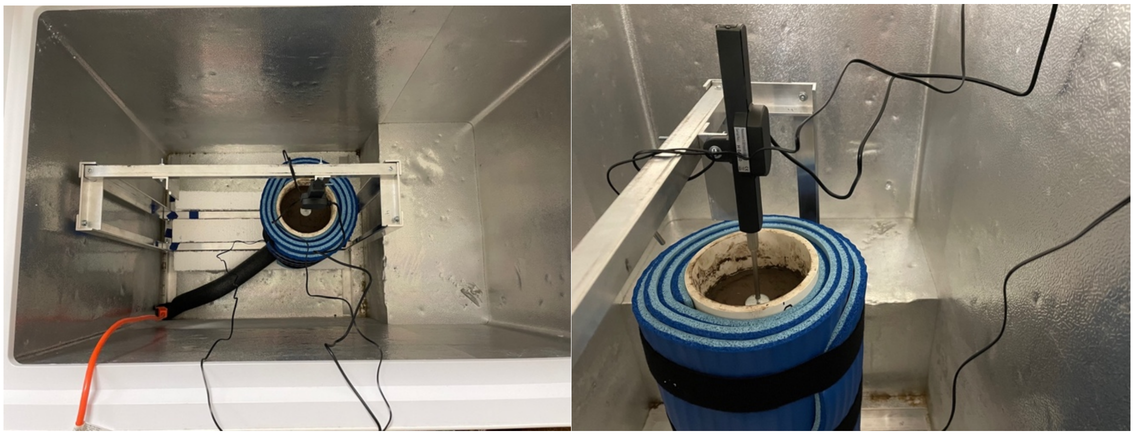
specimen to control and record the air and water temperatures and the change in specimen height, respectively, during testing. The temperature controllers and the displacement sensor reader, situated outside of the freezer during testing, are shown in Figure 7. During testing, the temperatures of the freezer and heat tape as shown on the temperature controllers and the displacement as shown on the displacement sensor reader were manually recorded several times per day together with the date and time. Figure 8 shows a specimen prepared for frost-heave testing within the apparatus, and Figure 9 shows a schematic in which the individual components of the apparatus are labeled. Both of the trial tests were continued for 10 days to enable an evaluation of the functionality of the apparatus.

Figure 7

Temperature Controllers and Displacement Sensor Reader

Figure 8

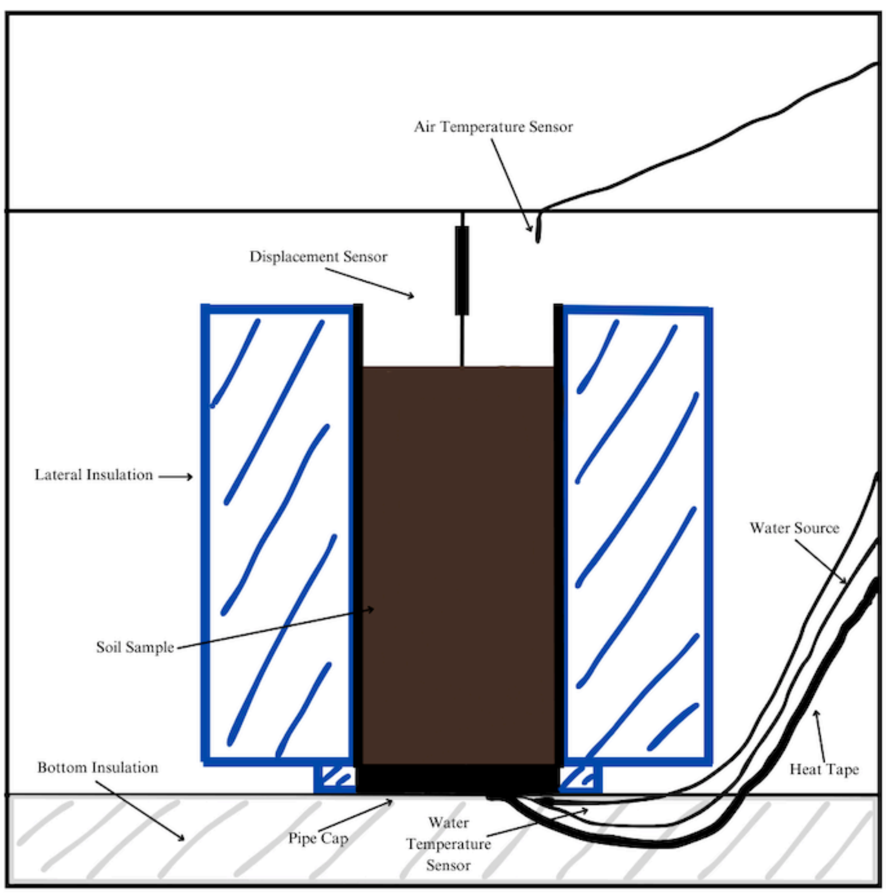
Specimen Prepared for Frost-Heave Testing: (a) Top View and (b) Side View



(a) (b)

Figure 9

Schematic of Frost-Heave Testing Apparatus



RESULTS

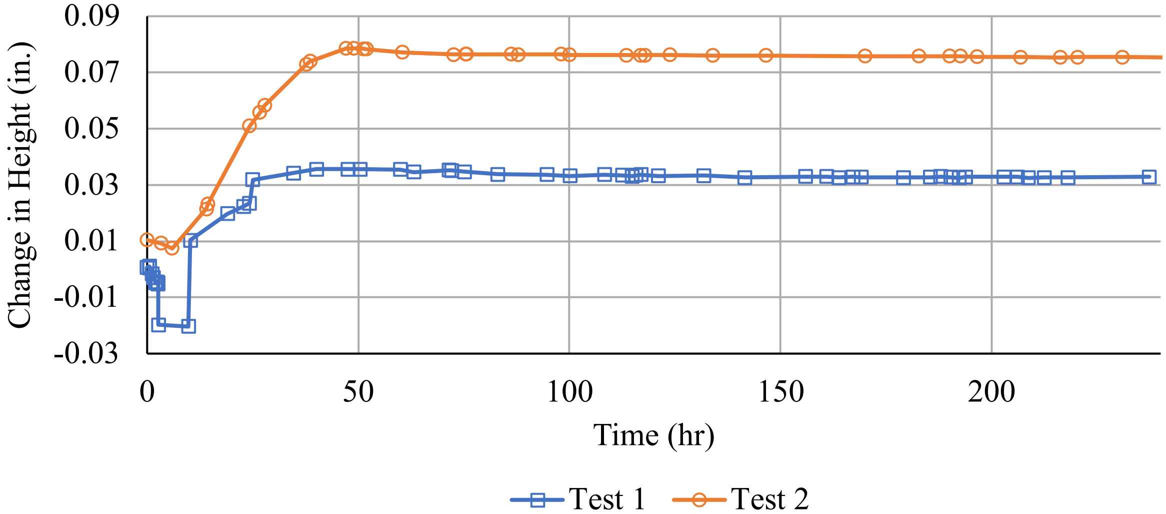
This section presents the results from the two trial tests that were performed to evaluate the functionality of the developed frost-heave testing apparatus. The clayey soil specimen used in the first test weighed 12.275 lb and 12.238 lb before and after testing, respectively, having lost 0.037 lb during testing; this weight loss may be attributable to evaporation of water from the specimen surface, which remained uncovered during testing, and the absence of water ingress during testing because of the low permeability of the clayey soil. The water level was initially set to be 2.375 in. above the bottom of the specimen and was later increased to 4.0 in. in an effort to increase the probability of heaving. The air and water temperatures were initially set at 21.2 °F and 37.4 °F, respectively. Data collected during frost-heave testing include readings taken at variable intervals during the test that consist of the date and time, displacement sensor reading, and temperatures of both the water and air as displayed on the temperature controllers; these data are provided in the appendix.

The silty soil specimen used in the second test weighed 11.75 lb and 12.37 lb before and after testing, respectively, having gained 0.62 lb during testing; this weight gain is likely attributable to the movement of water into the specimen during testing. A water table height of 2.375 in. was used for this test. The air and water temperatures were initially set at 17.6 °F and 34.7 °F, respectively, and the same method used for data collection in the first test was also used during this second test; these data are also provided in the appendix.

From the displacement data recorded during both tests, the graph in Figure 10 was developed to show the change in specimen height over time. As the displacement sensor

Figure 10

Change in Specimen Height During Testing

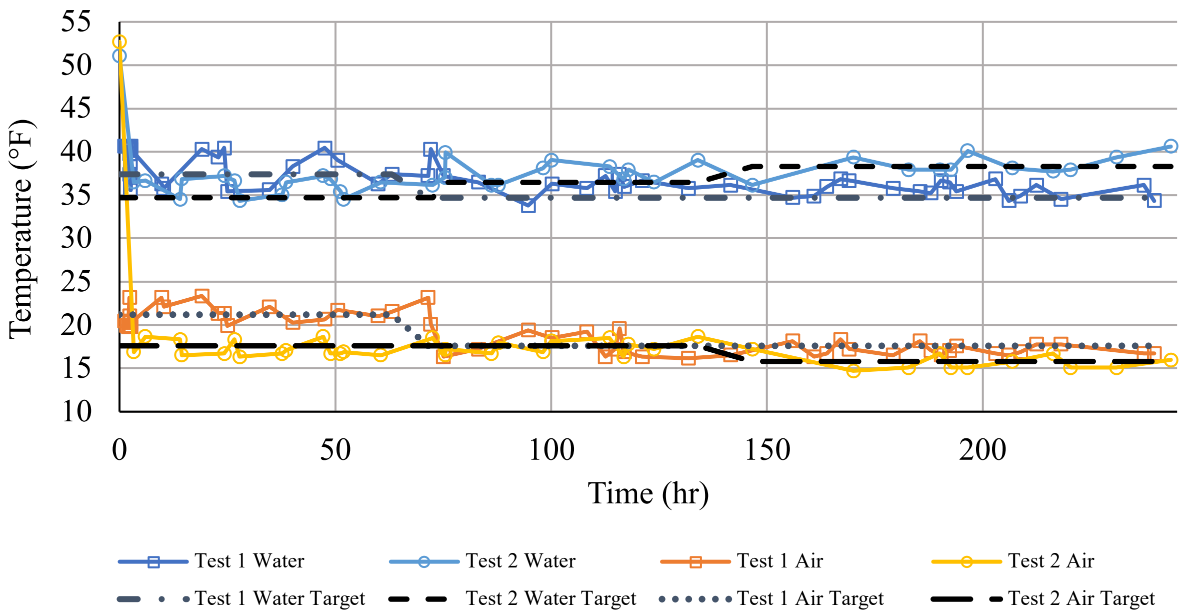


was deliberately not fully extended at the start of the tests, the initial readings were not zero. Therefore, to determine the change in specimen height over time, the initial reading was subtracted from all subsequent readings for each specimen. Additionally, because the displacement sensor reported readings in millimeters, all changes in specimen height were converted to inches prior to graphing. Figure 10 shows that, during the first 10 hours of the test, both specimens decreased in height as opposed to increasing in height. This response of the soil to the cold temperatures in each test is a reflection of the coefficient of thermal expansion of the soil. After this initial contraction, the first sample heaved approximately 0.036 in. and the second sample heaved approximately 0.078 in. relative to their initial heights. As expected, the silty soil heaved more than the clayey soil. These maximum increases in heights were achieved by approximately 50 hours of frost-heave testing; the specimen heights remained fairly constant after this time.

In addition to the graph showing the change in specimen height during testing, a graph showing the actual water and air temperatures, as compared to the target temperatures, was developed as shown in Figure 11. The temperature readings hovered near the target temperatures while reflecting the cyclical nature of the temperature controllers. In the first test, the target air and water temperatures were decreased at the 72-hour mark to 17.6 °F and 34.7 °F, respectively, where they remained for the duration of the testing. In the second test, the target air temperature was decreased at the 146-hour mark from 17.6 °F to 15.8 °F, and the target water temperature was increased at the 72-hour and 146-hour marks to 36.5 °F and 38.3 °F, respectively, where they remained for the duration of the testing. The apparatus was able to maintain the target temperatures to within 2.2 °F.

Figure 11

Water and Air Temperatures During Testing



While all of the components of the frost-heave testing apparatus functioned as designed, the interface between the heating system and the base of the specimen was determined to be insufficiently conductive. At the conclusion of both of the trial tests, ice was observed at the end of the water line where it was connected to the base of the specimen, even with some changes to the insulation around the water line in the second test. In addition, in the second test, the base of the specimen appeared to be at least partially frozen, with the frozen soil causing a downward expansion of the rubber cap. For these reasons, an improved means of transferring heat from the heating system to the base of the specimen is needed, and a proposed redesign will soon be implemented to prevent the water line and the base of the specimen from freezing.

CONCLUSION

The objective of this research was to develop and demonstrate an apparatus for assessing the frost-heave susceptibility of soil in a laboratory setting. The frost-heave testing apparatus developed in this study is similar in many respects to previous apparatuses as it provides a water supply and heat source at the bottom of the specimen, freezing conditions at the top of the specimen, and a displacement sensor to measure heave. It is unique, however, in that it can be constructed and operated without extensive computer programming, without repeated sensor calibrations, and without maintenance of a complex heating or cooling system while providing control over the both the water level and the temperature gradient during testing.

Development of the frost-heave testing apparatus required several components, including a freezing system, a heating system, temperature controllers, a metal frame, a water delivery system, and an insulated specimen container. For the freezing system, a chest freezer was selected to provide a test environment that can be maintained at an adjustable air temperature below 32 °F. For the heating system, thermostat-controlled heat tape was selected for positioning around the base of the specimen and along the water line inside the freezer. For temperature controllers, relays with integrated temperature sensors were selected and connected to the chest freezer and heat tape; independently controlling the air temperature inside the freezer and the water temperature at the base of the specimen enabled control of the temperature gradient across the length of the specimen.

For two trial 10-day frost-heave tests of clayey soil and silty soil, graphs were developed to show the change in specimen height over time and to show the actual water and air temperatures, as compared to the target temperatures. As expected, the silty soil heaved more than the clayey soil. The apparatus was able to achieve the target temperatures to within 2.2 °F. While all of the components of the frost-heave testing apparatus functioned as designed, the interface between the heating system and the base of the specimen was determined to be insufficiently conductive, with ice observed at the end of the water line where it was connected to the base of the specimens, and an improved means of transferring heat from the heating system to the base of the specimen is therefore needed; a proposed redesign will soon be implemented to prevent the water line and the base of the specimen from freezing.

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APPENDIX

Test 1

Date	Time (hh:mm)	Test Duration (hr)	Reading (mm)	Temperatures (°C)	
				Water	Air
2/20/24	8:15 PM	0.00	12.575	-	-
2/20/24	8:50 PM	0.58	12.595	-	-
2/20/24	8:51 PM	0.60	12.603	-	-
2/20/24	9:24 PM	1.15	12.589	4.8	-6.4
2/20/24	9:49 PM	1.57	12.536	4.8	-6.7
2/20/24	10:16 PM	2.02	12.497	4.8	-6.8
2/20/24	10:34 PM	2.32	12.453	3	-4.9
2/20/24	10:40 PM	2.42	12.458	4.3	-6.1
2/20/24	10:41 PM	2.43	12.459	4.7	-6.5
2/20/24	10:43 PM	2.47	12.458	4.3	-6.7
2/20/24	10:45 PM	2.50	12.457	3.7	-6.8
2/20/24	10:47 PM	2.53	12.453	2.8	-6.8
2/20/24	10:49 PM	2.57	12.449	2	-6.8
2/20/24	10:51 PM	2.60	12.445	4.8	-6.8
2/20/24	10:54 PM	2.65	12.44	4.6	-6.5
2/21/24	6:01 AM	9.77	12.072	2.4	-4.9
2/21/24	6:30 AM	10.25	12.057	2.1	-5.5
2/21/24	3:19 PM	19.07	12.837	4.6	-4.8
2/21/24	7:09 PM	22.90	13.078	4.1	-5.9
2/21/24	8:31 PM	24.27	13.143	4.7	-5.9
2/21/24	9:15 PM	25.00	13.173	1.9	-6.7
2/22/24	7:00 AM	34.75	13.383	2	-5.5
2/22/24	12:22 PM	40.12	13.443	3.5	-6.5
2/22/24	7:48 PM	47.55	13.478	4.7	-6.3
2/22/24	10:45 PM	50.50	13.478	3.9	-5.7
2/23/24	8:13 AM	59.97	13.48	2.4	-6.1
2/23/24	11:23 AM	63.13	13.475	3	-5.8
2/23/24	7:45 PM	71.50	13.452	2.9	-4.9
2/23/24	8:19 PM	72.07	13.47	4.6	-6.6
2/23/24	11:20 PM	75.08	13.469	2.9	-8.7
2/24/24	7:21 AM	83.10	13.455	2.5	-8.2
2/24/24	6:57 PM	94.70	13.432	1	-7
2/25/24	12:24 AM	100.15	13.43	2.4	-7.5
2/25/24	8:32 AM	108.28	13.419	2.1	-7.1
2/25/24	12:50 PM	112.58	13.431	2.9	-8.7
2/25/24	3:06 PM	114.85	13.423	1.9	-8.2
2/25/24	4:04 PM	115.82	13.416	3	-6.9
2/25/24	5:12 PM	116.95	13.424	2.2	-8.4

Date	Time (hh:mm)	Test Duration (hr)	Reading (mm)	Temperatures (°C)	
				Water	Air
2/25/24	9:21 PM	121.10	13.429	2.6	-8.7
2/26/24	8:05 AM	131.83	13.419	2.1	-8.8
2/26/24	5:47 PM	141.53	13.42	2.3	-8.6
2/27/24	8:11 AM	155.93	13.404	1.5	-7.7
2/27/24	2:08 PM	160.88	13.414	1.6	-8.7
2/27/24	5:07 PM	163.87	13.414	2.2	-8.5
2/27/24	8:20 PM	167.08	13.403	2.7	-7.6
2/27/24	10:20 PM	169.08	13.411	2.6	-8.2
2/28/24	8:26 AM	179.18	13.408	2.10	-8.60
2/28/24	2:41 PM	185.43	13.403	1.90	-7.70
2/28/24	5:11 PM	187.93	13.407	1.8	-8.3
2/28/24	7:34 PM	190.32	13.413	2.6	-8.6
2/28/24	9:35 PM	192.33	13.408	2.5	-8.3
2/28/24	11:07 PM	193.87	13.402	1.9	-8
2/29/24	8:11 AM	202.93	13.41	2.7	-8.5
2/29/24	11:18 AM	206.05	13.411	1.3	-8.6
2/29/24	1:57 PM	208.70	13.41	1.6	-8.4
2/29/24	5:41 PM	212.43	13.402	2.3	-7.9
2/29/24	11:21 PM	218.10	13.404	1.4	-7.9
3/1/24	6:34 PM	237.32	13.404	2.3	-8.5
3/1/24	8:57 PM	239.70	13.41	1.3	-8.5

Test 2

Date	Time (hh:mm)	Test Duration (hr)	Reading (mm)	Temperatures (°C)	
				Water	Air
3/5/24	6:07 PM	0	13.674	10.6	11.5
3/5/24	9:24 PM	3.28333333	13.647	2.5	-8.4
3/6/24	12:03 AM	5.93333333	13.598	2.6	-7.4
3/6/24	8:11 AM	14.0666667	13.956	1.4	-7.6
3/6/24	8:33 AM	14.4333333	14.003	2.7	-8.6
3/6/24	6:25 PM	24.3	14.705	2.9	-8.5
3/6/24	8:48 PM	26.6833333	14.827	2.6	-7.6
3/6/24	9:57 PM	27.8333333	14.891	1.3	-8.7
3/7/24	7:47 AM	37.6666667	15.261	1.7	-8.5
3/7/24	8:40 AM	38.6166667	15.29	2.5	-8.3
3/7/24	5:14 PM	47.1833333	15.406	2.9	-7.4
3/7/24	6:57 PM	48.9	15.406	2.7	-8.5
3/7/24	9:15 PM	51.2	15.401	1.9	-8.5
3/7/24	10:00 PM	51.95	15.398	1.4	-8.4
3/8/24	6:34 AM	60.5166667	15.369	2.5	-8.6
3/8/24	6:37 PM	72.5666667	15.35	2.3	-7.5
3/8/24	9:30 PM	75.45	15.353	2.8	-8.6
3/8/24	9:35 PM	75.5333333	15.352	4.4	-8.2
3/9/24	8:15 AM	86.2	15.353	2.3	-8.5
3/9/24	9:52 AM	87.8166667	15.349	2.3	-7.8
3/9/24	8:09 PM	98.1	15.352	3.4	-8.4
3/9/24	9:55 PM	100.033333	NA	3.9	-7.7
3/10/24	11:27 AM	113.566667	15.344	3.5	-7.5
3/10/24	2:39 PM	116.766667	NA	2.7	-8.7
3/10/24	3:47 PM	117.9	15.345	3.3	-7.9
3/10/24	9:45 PM	123.866667	15.346	2.5	-8.2
3/11/24	7:51 AM	133.966667	15.341	3.9	-7.4
3/11/24	8:27 PM	146.566667	15.341	2.3	-8.2
3/12/24	7:56 PM	170.05	15.337	4.1	-9.6
3/13/24	8:37 AM	182.733333	15.337	3.3	-9.4
3/13/24	3:53 PM	190	15.336	3.3	-8.5
3/13/24	6:29 PM	192.6	15.335	3.3	-9.4
3/13/24	10:23 PM	196.5	15.331	4.5	-9.4
3/14/24	8:42 AM	206.816667	15.327	3.4	-9
3/14/24	6:08 PM	216.25	15.325	3.2	-8.5
3/14/24	10:15 PM	220.366667	15.326	3.3	-9.4
3/15/24	8:52 AM	230.983333	15.326	4.1	-9.4
3/15/24	9:26 PM	243.55	15.324	4.8	-8.9