

EFFECT OF SOIL PROPERTIES AND CLIMATIC CONDITIONS
ON FROST ACTION IN SOILS

By

Md Fyaz Sadiq

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ABSTRACT

In cold regions, frost action can significantly impact roadway performance due to frost heave and thaw settlement of the subgrade soils. The severity of the damage depends on the soil properties, temperature, freeze-thaw cycles, and water availability. While nominal expansion occurs with the phase change from pore water to ice, heaving is derived primarily from a continuous water flow from the vadose zone to growing ice lenses. The temperature gradient within the soil influences water migration towards the freezing front during winter, where ice nucleates, coalesces into lenses, and grows. When the temperature increases during the spring season, the ice melts, inducing thaw settlement and causing a reduction in soil strength. This study investigated the effect of soil properties, including the gradation and soil thermal properties (thermal conductivity, specific heat, thermal diffusivity), on the frost susceptibility of soils from Iowa and North Carolina through the laboratory frost heave and thaw settlement test. Total heave, heave rate, temperature profile, frost penetration depth, and frost penetration rate were measured as a function of time. The results showed that soils that had higher silt content had higher heaving. Maximum frost penetration rate was observed for soils with higher thermal diffusivity. Moreover, the impact of climatic conditions on frost heave was assessed by conducting tests under varying conditions of water availability (open vs. closed system), multiple freeze-thaw cycles, and temperature gradients. It was observed that the presence of an external water source significantly increased the magnitude of heave, resulting in a seven times higher total heave compared to those soils in a closed system. The soil specimens experienced a continuous increase in heave until the sixth freeze-thaw cycle, after which it stabilized. The freezing process caused the soil specimens to exhibit a high rate of water intake, which decreased during thawing. Under extended freezing periods, both soils showed the maximum total heave when subjected to a lower temperature gradient. The silty sand/silty clay soil experienced more significant frost heave and water intake volume compared to low plasticity clay, owing to its high hydraulic conductivity.

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CHAPTER 1: GENERAL INTRODUCTION

In cold climate regions, roadways are significantly impacted by the annual freeze-thaw cycles. Frost heaving and thaw weakening are closely linked yet they are distinct processes that both are used to characterize frost action in the soil. Frost heaving occurs due to the formation and growth of pore ice, while thaw weakening occurs due to the subsequent melting of ice crystals. These phenomena lead to soil saturation, a decrease in bulk density, and a consequent reduction in the load-carrying capacity of roadways (Simonsen & Isacsson, 1999).

Two primary mechanisms characterize frost heave. First, the pore water undergoes a 9% volume expansion upon freezing due to the difference in density between liquid and solid water states. Second, ice lenses are formed through nucleation and growth of segregated ice resulting from water migration, which appears as distinct stripes of pure ice (Li et al., 2014; Taber, 1929). The primary mechanism, the freezing of pore water, is known as the primary heave. The freezing of water resulting from the mass transfer is classified as secondary heave, also known as segregational heave. Segregated ice forms due to the movement of liquid pore water from unfrozen regions toward the actively freezing interface (Casagrande, 1931; Taber, 1929). The thickness of the ice lens is influenced by the presence and movement of pore water and the duration of the freezing period. Under in-situ conditions, the secondary mechanism, also known as secondary frost heave, dominates the volumetric expansion of water upon freezing (Fowler, 1989). Frost heave is contingent upon three conditions: the presence of a water source (e.g., high water table or any water supply), a frost-susceptible soil (i.e., soil that can supply water to the freezing front through capillary action), and temperatures below freezing point (Penner, 1959; Taber, 1929). Furthermore, there must be a temperature gradient to initiate water intake by the soil (Zhang et al., 2017).

Everett (1961) introduced the capillary theory to explain water movement during frost heave, proposing that capillary action was the primary mechanism driving soil uptake of external water. However, this hypothesis failed to account for the growth of discrete ice lenses and underestimated the heaving force in fine-grained soil (Miller, 1972; Peppin & Style, 2013; Wang et al., 2018). To address these limitations, Miller (1972) presented the frozen fringe theory, which was subsequently expanded upon by Gilpin (1980) and Konrad & Morgenstern (1980). The authors proposed the existence of a region called the frozen fringe, located between the warmest ice lens and the freezing front. The frozen fringe facilitates the formation of ice lenses by allowing

water to move from unfrozen soil to frozen soil (Miller, 1972; Nixon, 1992). The frozen fringe maintains a temperature between 0 and -2 °C, which is lower than the bulk freezing point of water, but does not contain ice lenses (Tiedje, 2015). The coexistence of pore ice and pore water enables the formation of ice lenses consistently and slowly. When water flows in frozen soil in the direction of decreasing temperature, the rate is determined by the suction force of the frozen fringe and the hydraulic conductivity of the frozen soil. The suction at the ice-water interface is termed as cryogenic suction (Thomas et al., 2009), which causes pore water to flow and is the key force that induces the formation of an ice lens in frozen soil (Doré, 2004). Takagi (1979) proposed that a suction force draws water toward the frozen surface. According to his theory, water in the soil can exist in two forms: water in the pores and adsorbed water across the solid grains. The thin water film retains its thickness when frozen due to interparticle interactions. The Gibbs-Thomson effect causes a small amount of unfrozen water to remain between the ice grains and surfaces of soil grains. This leads to a decrease in freezing temperature because of the high curvature of the ice-liquid interface in small pores (Williams, 1964). The maximum reduction of the freezing point below 0° C occurs in water that is most firmly held and adjacent to soil particles. This thin layer of unfrozen water causes negative pressure (suction) that pulls water from the surroundings.

Over the years, researchers classified the frost susceptibility of soils by examining various factors such as particle size distribution, moisture content, and plasticity testing (Chamberlain, 1981a; US Army Corps of Engineers, 1965). However, the effectiveness of this approach varies depending on the soil type and the prevailing climatic conditions. For instance, Beskow (1991) observed that frost heaving decreases as particle size increases in coarse silty clays, while it decreases with decreasing grain size in fine-grained soil. Chamberlain (1981) identified several methods for classifying soils based on frost heave. Still, these methods were developed based on specific soil and climatic conditions, and, as a result, the classifications vary from one region to another. Moreover, the impact of multiple freeze-thaw cycles is not well understood in the literature, and previous studies (Loch & Kay, 1978; Zhang et al., 2017) examining the effect of temperature gradients on frost action do not represent field conditions. Therefore, a comprehensive assessment of the frost action is required, encompassing the widely used test procedures.

1.1 Research Goal and Objectives

The objectives of this proposed study are to (1) investigate the influence of gradation on the frost susceptibility of soils; (2) evaluate the effects of multiple freeze-thaw cycles on frost heave; (3) provide quantitative comparisons of frost heave under closed and open system; (4) investigate the effect of temperature gradient and soil thermal properties on frost action. To achieve these objectives, the experimental program consists of the following tasks:

1. Determining the physical properties of the soils used in this study by exploiting particle size distribution, Atterberg limit tests, and compaction,
2. Determining thermal properties of the soils by using KD2 Pro thermal properties analyzer,
3. Performing frost heave tests on soils from different regions following ASTM D5918, which involves subjecting the soils to two freeze-thaw cycles, an open system, and a temperature gradient of $0.78\text{ }^{\circ}\text{C/cm}$,
4. Performing frost heave tests by subjecting different soils to ten freeze-thaw cycles under open and closed systems,
5. Performing frost heave tests under different temperature gradients for extended periods of freezing,

Overall, the proposed study aims to advance the understanding of the complex mechanisms governing frost action in soils, with the ultimate goal of improving our ability to predict and mitigate the impacts of frost on infrastructure and the environment.

1.2 Organization of the Dissertation

This dissertation comprises five chapters: a general introduction, three research papers, and conclusions and recommendations. Chapter 1 provides a broad overview of the research by providing a general introduction that outlines the purpose and goals of the study. Chapter 2 explores the frost susceptibility of four different soils from Iowa and its relationship with soil gradation. Chapter 3 describes the behavior of silty sand/silty clay and low-plasticity clay under multiple freeze-thaw cycles in open and closed systems. Chapter 4 studies the influence of temperature gradient and soil thermal properties on frost heave. Chapter 5 summarizes the key findings of this study.

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CHAPTER 2: INFLUENCE OF GRADATION ON THE FROST SUSCEPTIBILITY OF SOILS

2.1 Abstract

Frost heave creates systemic failures in roadways, buried pipelines, and cold storage facilities across the United States and around the world. Significant frost heaving may occur when the following three conditions are met: (1) there are sustained freezing conditions, (2) the soil is frost-susceptible (typically silt-sized), and (3) there is access to water. Under these conditions and depending on the temperature gradient, pore water freezes into ice lenses that grow in the direction of heat loss, causing heave. When the temperature increases during the spring season, the ice melts, inducing thaw settlement and causing a reduction in soil strength. The nature and extent of frost heave vary according to water availability, pore fluid composition, rate of heat loss, and soil type. Likewise, soil properties influence the rate at which water is attracted to a growing ice lens and the temperature at which ice formation occurs. Laboratory tests can discern the significance of freezing intensity and duration as well as soil properties, including mineralogy, grain-size distribution, and pore fluid. As part of a larger nationwide project, the current study evaluates the frost heave potential of soils collected from four different regions in Iowa. Cylindrical soil samples were given free access to water and subjected to two freeze-thaw cycles. Total heaving, heave rate, temperature profile, frost penetration depth, and its rate were measured as a function of time. Water intake during testing was also measured for Pottawattamie County soils. The results of the study showed that the amount of silt content in the soil has a direct effect on the frost heave phenomenon. Soils that have higher silt content had higher heaving. It was determined that all the soils were highly frost susceptible and had high heave rates of up to 26.3 mm/day. The maximum frost penetration rate was 14.3 mm/hour for the soil specimen from Pottawattamie County(IA-PC).

2.2 Introduction

Frost action may contribute to the rapid deterioration of pavements and other geo-structures and has a substantial impact on the geotechnical properties of soils (Qi et al., 2006; Cui et al., 2014; Mahedi et al., 2020). The U.S. Federal Highway Administration allocates around 30% of the maintenance budget to the damage caused by frost action in the pavement in cold countries (PIARC Technical Committee 2015). This action in the soil can be described by two different but

correlated processes, frost heaving and thaw weakening. Frost heave is instigated by the change in the phase of water, which results in the formation of ice lenses in a soil matrix, while thaw weakening results from the melting of ice crystals which may cause saturation in the soil and subsequent loss in bearing capacity during thawing process (Simonsen and Isacsson 1999). Ice lenses cause volume expansion in the soil leading to heaving (Rosa et al. 2017). It is a common phenomenon primarily in the silty soils in cold climatic regions as freezing temperatures (below 0° Celsius or prevailing freezing point) transmit beneath the ground surface (Washburn 1956). In fact, the formation of ice lenses in frozen soil begins marginally lower than 0 °C temperature (Miller 1972; Konrad and Morgenstern 1982). This challenge due to frost action is more acute in seasonally frozen areas (Cetin et al. 2019).

Fine-grained texture and high porosity cause frost susceptibility in soils with high silt content, as these characteristics enable soils to have higher moisture content and higher hydraulic conductivity. The frost susceptible soil classification of the U.S. Army Corps of Engineers based on the grain size distribution is the most widely used. Although the classification predicts the frost susceptibility of the soil, the interaction between the soil and environmental conditions is significant to the frost heave process. Frost heaving rate and ice lens formation depend on environmental factors such as pore fluid composition, temperature gradient, location of the water table, effective vertical stress, and cooling rate (Sheng et al. 2013). Konrad (1989) investigated the effect of the rate of cooling on the initiation temperature of the ice lens and observed that the ice lens initiated at a warmer temperature when the cooling rate decreased. Thus, a rise in cooling rate during a fixed freezing time usually results in higher frost penetration depth and more significant frost heave (Sheng et al. 2013).

In this study, one-dimensional freezing experiments were conducted on soil specimens obtained from four distinct regions of Iowa, including Buena Vista County, Clinton County, Keokuk County, and Pottawattamie County. The frost heave and thaw settlements of these soils were measured for two freeze-thaw cycles under a constant cooling and warming rate. The change in temperature of the soil was monitored with six thermocouples placed inside the specimens. The temperature profile of soil and heaving trends was monitored during freezing and thawing periods. The water intake during the testing was also observed for the Pottawattamie County soil. During the experimental testing, the parameters employed for evaluation included total heave, heave ratio,

frost penetration depth, and frost penetration rate. The temperature profile of the soil and the water inflow rate was correlated with the heaving trend during the freezing period.

2.3 Materials and Methods

The soils were collected from Buena Vista County(IA-BV), Clinton County(IA-CC), Keokuk County(IA-KC), and Pottawattamie County(IA-PC) in Iowa. All the index properties of soils were determined by following proper ASTM methods (ASTM D854-14, ASTM D6913-17, ASTM D7928-21e1, ASTM D4318-17, ASTM D698-12, ASTM D5918-13e1). The relevant index properties and classification of soils are shown in Table 2.1. The grain size distributions of the soils are presented in Figure 2.1.

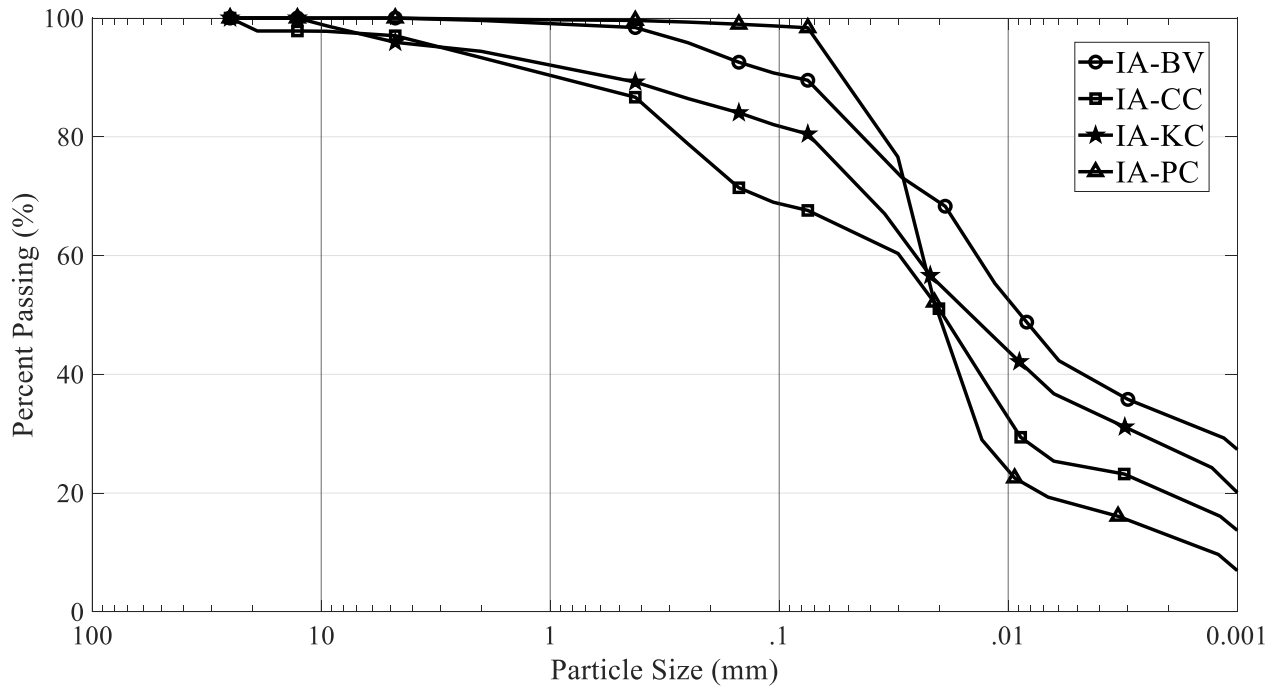


Figure 2. 1 Grain size distribution of the soils

Table 2. 1 Physical properties of the soils

Soil Properties	IA-BV	IA-CC	IA-KC	IA-PC
Specific Gravity, G_s (ASTM D854-14)	2.69	2.63	2.70	2.80
Liquid Limit, LL (%) (ASTM D4318-17)	67	52	40	37
Plasticity Index, PI (%) (ASTM D4318-17)	41	28	15	13
Silt content (%) ($75\ \mu\text{m}-2\ \mu\text{m}$)	57.6	48.7	54.8	86.2
Clay content (%) ($< 2\ \mu\text{m}$)	32	19	27	12
Optimum Moisture Content (%) (ASTM D698-12)	27.1	19.6	17.2	17.3
Max. Dry Unit Weight (kN/m^3) (ASTM D698-12)	13.8	15.9	16.6	16.7
USCS Classification (ASTM D2847)	CH	CH	CL	CL
AASHTO Classification	A-7-6	A-7-6	A-6	A-6
Frost Susceptibility Group ⁺	F3	F3	F3	F3

*N.P.- Non-Plastic

+ Frost susceptibility classification by U.S. Army Corps of Engineers (1965) based on grain size distribution.

F1-Low frost susceptibility; F4-Very high frost susceptibility

The frost heave testing of soil specimens was conducted as per ASTM D5918. The soil specimens were oven-dried and then compacted, with 40 blows in 5 layers, at their optimum moisture content (OMC) for maximum dry density (MDD) into a 14.6 cm diameter and 15.2 cm height sample. The specimens were wrapped with a latex membrane and six acrylic rings before compaction and were then placed on a base plate, which was connected to the Mariotte cylinder as a water supply source. The specimens were then saturated for 24 hours as per the ASTM method, regardless of the degree of saturation at the end of the saturation. After the saturation period, the specimens were placed into the chest freezer.

Each specimen was set on a heat exchange plate that was connected to a circulating bath. Another heat exchange plate, also attached to a circulating bath, was placed at the top of the specimens to replicate ground freezing conditions. Two AP28R-30 circulating baths from PolyScience were used for the experiment. The fully programmable units have a capacity of 28

Liters and has a temperature range of -30°C to 200°C . Both units were filled with ethylene glycol and water solution (at a ratio of 1:1). The cooling capacity of the circulating baths at 0°C was 505 Watts (W). The temperature program in the circulating baths for the top and bottom heat exchange plate is shown in Figure 2.2. This program is provided as an input to the circulating bath; however, the temperature change may take some time to reduce from higher to lower temperature and vice versa. For example, it was observed that the temperature change from -3°C to -12°C of circulating fluid took 30 minutes during testing. A surcharge weight of 5 kg was placed at the top of the specimen above the top heat exchange plate. The Mariotte water supply was placed alongside the specimen to provide a constant water source during the experiment. It was connected to the specimen's base plates. The heaving of the specimens during the experiment was measured using laser sensors. The laser sensors used in the experiment were OptoNCDT 1750 from Micro-Epsilon. The laser sensor has a measuring range of 50 mm and provides high accuracy with real-time data. 6 T-type thermocouples were inserted inside each soil specimen that was spaced vertically every 2.5 cm. The temperature of the freezer was controlled using an electronic temperature control unit. The freezer was programmed to maintain a 4°C temperature. The freezer was filled with packing peanuts to completely cover the soil specimens to have a controlled environment and minimize lateral heat loss so only 1D freezing occurs.

The thermocouple and laser sensors were connected to a data acquisition system consisting of a CR1000X data logger and AM16/32B multiplexer. PC400 software was used for data monitoring and collection. The pressure transducers were also used to measure the water intake during different stages of the freezing and thawing cycle. Figure 2.3 shows the schematic diagram of the assembly inside the freezer. All the hoses for connecting different parts were wrapped with thermal insulation tape to minimize heat loss and better environmental control. The capillary tube in the Mariotte water supply was placed 1.3 cm above the specimen's bottom plate during testing to maintain a constant head. The five-day testing was conducted by applying two freeze-thaw cycles on each specimen.

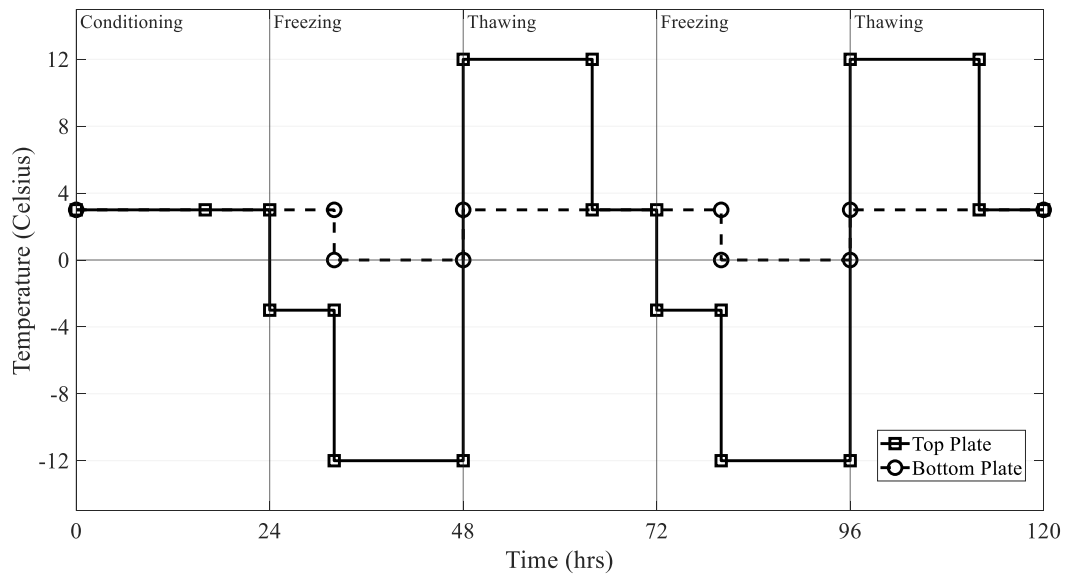


Figure 2. 2 Temperature program in circulating bath for top and bottom heat exchange plates

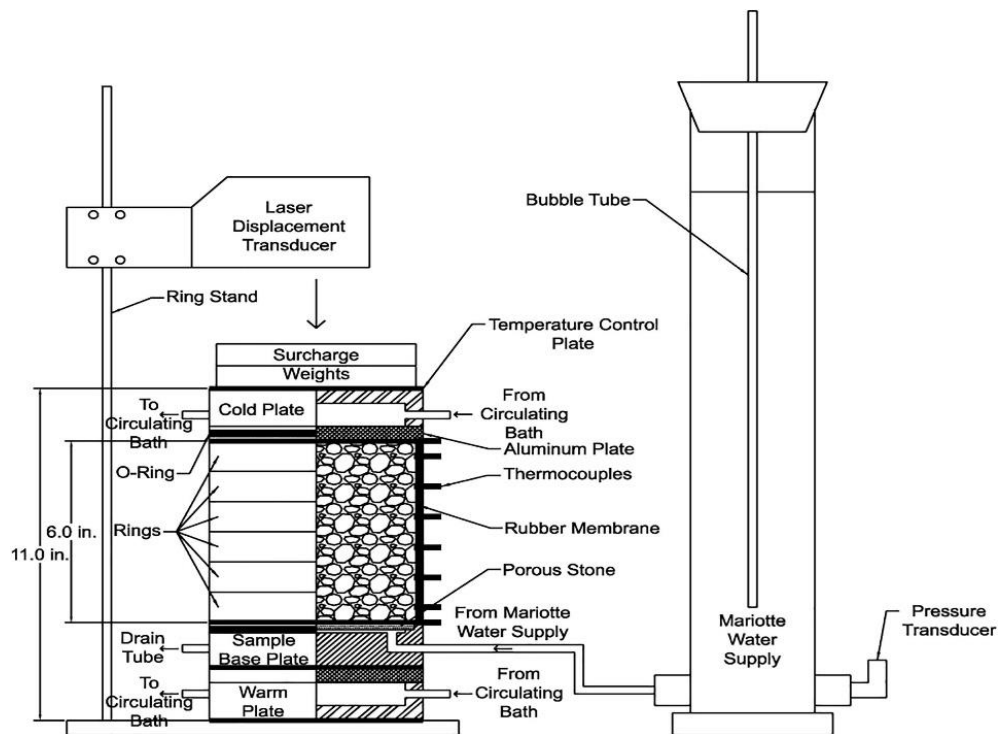


Figure 2. 3 Frost heave testing setup (Mahedi et al. 2020)

2.4 Total Heaving, Heave Rate, Heave Ratio

The trend of frost heave-thaw settlement plots for four soils is illustrated in Figure 2.4. As expected, all soils experienced heaving during freezing and consolidation during thawing cycles. The first 24 hours of testing provide a conditioning period with both bottom and top heat exchange plates at above-freezing temperatures. After this conditioning period, the first freezing cycle (24 hours) and thawing cycle (24 hours) began. No heaving was observed in IA-BV, IA-CC, and IA-PC soils during the first 8 hours of freezing. This is due to the low-temperature gradient in the first 8 hours of freezing. In addition, the subsequent effect of this temperature drop in the soil may take some time, depending on the thermal conductivity of the soil. Besides, ice nucleation sometimes requires a physical disturbance, e.g., through specimen vibration (Daniels et al. 2003). Only IA-KC soil showed heaving during the first 8 hours of the freezing period. It is believed that the high thermal conductivity of the soil may have induced heaving even with this low-temperature gradient. However, substantial heaving starts in all soils after the first 8 hours of the freezing period. It is because the top heat exchange plates temperature was changed from -3°C to -12°C , which is significantly below the freezing temperature causing substantial ice lens formation and subsequent heaving. All the soils followed similar heaving and thawing trends during the test. All the soils showed higher heaving in the second cycle compared to the first cycle. For IA-BV, IA-KC, and IA-PC, the heaving is significantly higher in the second cycle because of the high silt content. On the other hand, IA-CC heaved less during the first and second freezing cycles due to the presence of lower silt content compared to the other three soils. These results suggest that high silt content of the soils causes higher total heaving. The increase in the heave of the soils during the second freeze-thaw cycle may be attributed to the increase in hydraulic conductivity of the soil after the first freeze-thaw cycle (Othman and Benson 1992). Due to the formation of cracks during the first freezing cycle (because of ice formation), the cross-sectional area available to flow increases causing higher hydraulic conductivity. Due to this higher hydraulic conductivity, the water availability is higher in the frozen fringe leading to further growth in the ice lens formation and thus leading to higher heave in the second freezing cycle.

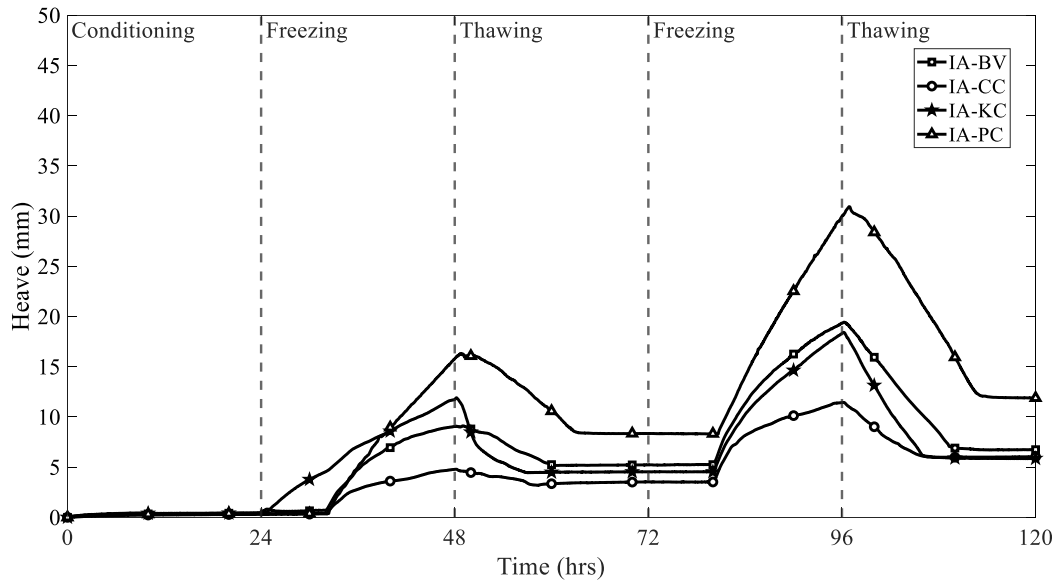


Figure 2. 4 Heave and thaw of different soils during frost heave testing

The total heave amounts and heave rates of different soils during the first and second freezing periods are presented in Figures 2.5 and 2.6. Figure 2.5 shows a quantitative comparison of the total heaving of each soil type at each freezing cycle. The results indicate that each soil has a different total heaving amount. The maximum heave was observed for IA-PC soils with 16.31 mm in the first cycle, while the minimum was observed for IA-CC soil (4.79 mm) in the first freezing cycle. The high heaving in IA-PC soil may be attributed to high silt and low clay contents. The silt particles and their high porosity provide an affinity for high moisture content and may yield more water for more significant ice formation and result in higher heaving (Pollard, 2017). However, the low hydraulic conductivity and low capillary action of IA-CC due to low silt content could explain lower heaving in the soil. Because of the low silt content, the soil has a low permeability reducing the extent to which water flows into the frozen fringe. This inhibits the growth of ice lenses (Sheng et al., 2013). Figure 2. 6 shows the heave rate of soils which is obtained by drawing a tangent line to the heaving curve as described by Zhang et al. (2016). Similar to the total heave trend, the maximum heave rate was also observed for IA-PC soil, whereas the minimum heave rate was observed for IA-CC. The heave rates observed for IA-BV, IA-CC, IA-KC, and IA-PC were 10.78 mm/day, 5.67 mm/day, 11.41 mm/day, 17.88 mm/day, respectively, for the first freezing cycle, and 17.77 mm/day, 10.22 mm/day, 16.86 mm/day and 26.27 mm/day, respectively for the second freezing cycle. According to the U.S. Army Corps of Engineers Frost susceptibility

classification, which is based on heave rate, all the soils tested exceed the very high frost heave criteria (>8.5 mm/day), making them highly frost susceptible soils.

The frost heave ratio is defined as the ratio of the total frost heave amount at the end of the test to the initial length of the samples at the start of the test. The frost heave ratios of IA-BV, IA-CC, IA-KC, and IA-PC were determined to be 4.4%, 3.9%, 3.8%, and 7.8%, respectively.

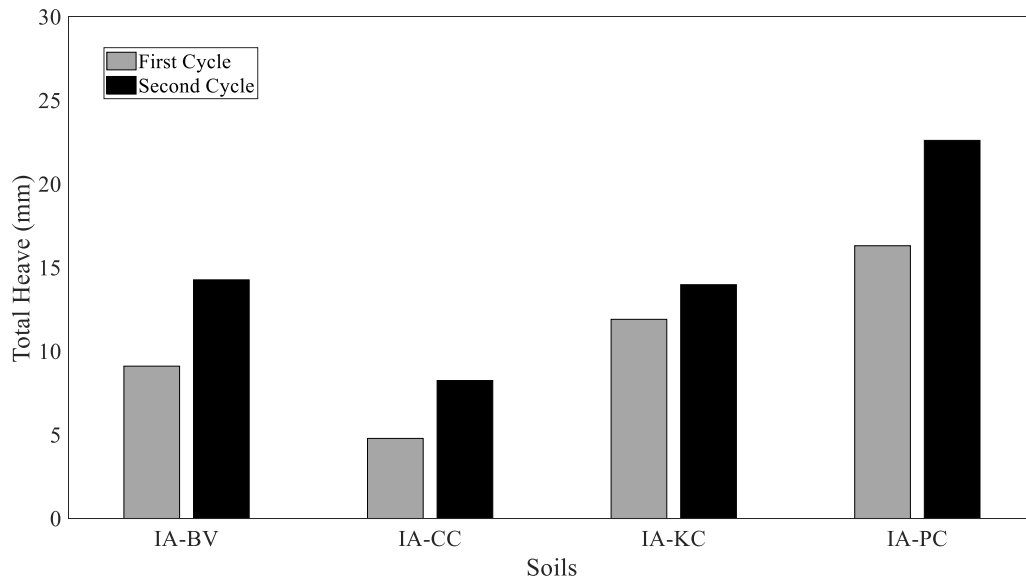


Figure 2. 5 Total heave of the soil specimens

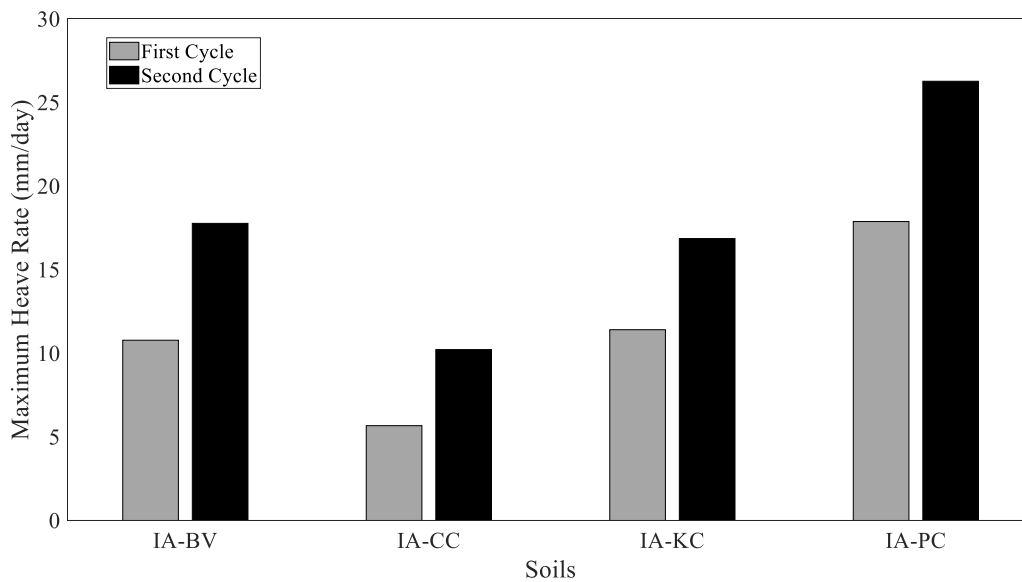


Figure 2. 6 Heave rate of the soil specimens

2.5 Frost Penetration Depth and Rate

The temperature distributions of IA-BV, IA-CC, IA-KC, and IA-PC soil specimens at various depths are shown in Figures 2.7, 2.8, 2.9, and 2.10. Six thermocouples were evenly spaced at 2.54 cm intervals, with the top thermocouple situated 1.3 cm below the specimen's surface. The results indicate that the maximum frost penetration depths during the two cycles were 11.4 cm, 13.9 cm, 13.9 cm, and 13.9 cm from the top for IA-BV, IA-CC, IA-KC, and IA-PC soil, respectively.

The freezing front, denoted by the zero-degree isotherm, progresses from top to bottom, as illustrated in Figure 2.7-2.10. Temperature fluctuations are more pronounced in the top section of the specimens, with the variations declining towards the bottom of the soil specimens as a top-down freezing experiment was conducted simulating the field conditions. Sharp trends in temperatures profile are also observed at the start of freezing and thawing periods.

The frost penetration rate is defined as the rate at which freezing isotherm moves into the specimen, which for these experiments is presumed to be 0° C (Chamberlain, 1981). Therefore, the ice lens formation was assumed to start at 0° C, and the freezing point depression was neglected for the calculation. IA-PC showed the highest frost penetration rate, followed by IA-BV, IA-CC, and IA-KC, with 14.3 mm/hour, 9.5mm/hour, 7 mm/hour, and 6.9 mm/hour, respectively. The frost penetration rate and depth depend on the soil thermal properties (thermal conductivity, specific heat, and thermal diffusivity).

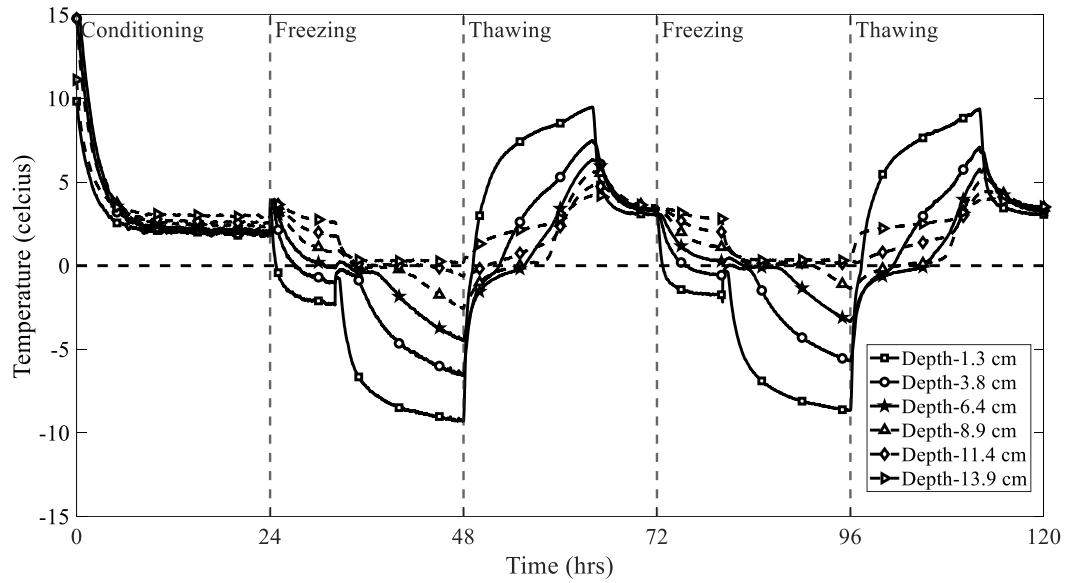


Figure 2. 7 Temperature profile of the IA-BV specimen

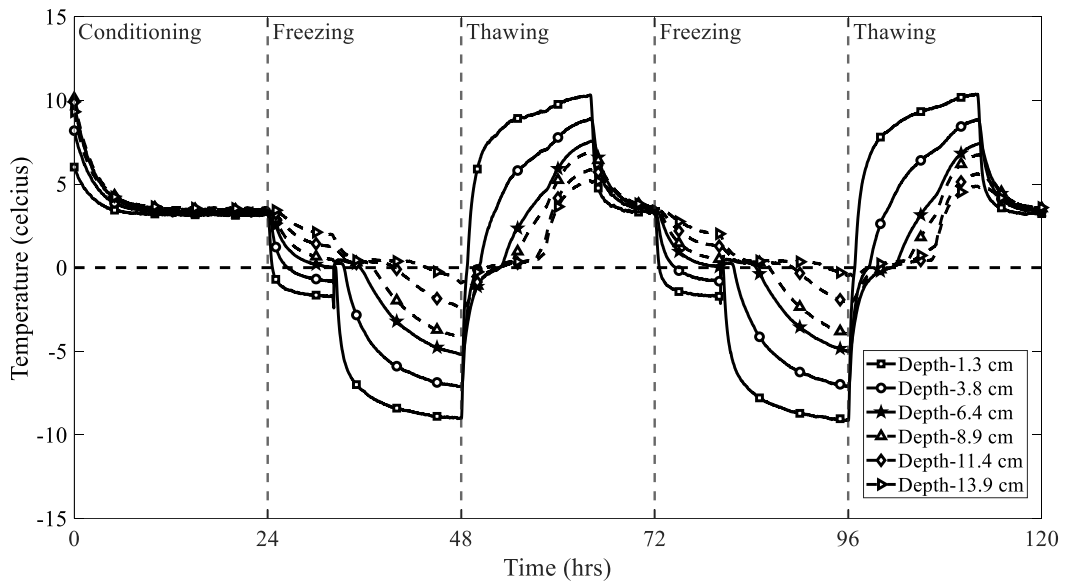


Figure 2. 8 Temperature profile of the IA-CC specimen

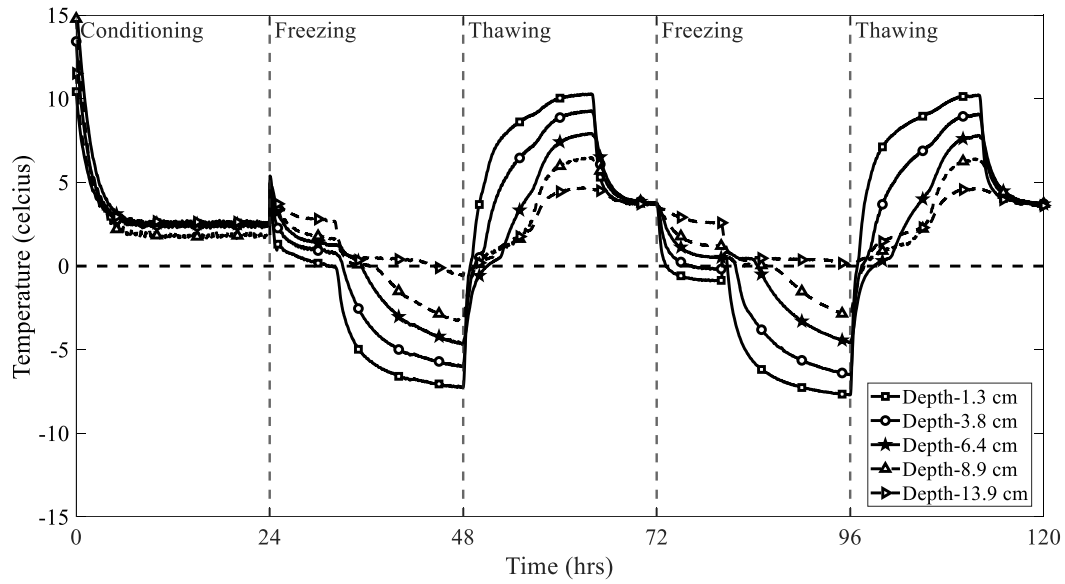


Figure 2. 9 Temperature profile of the IA-KC specimen

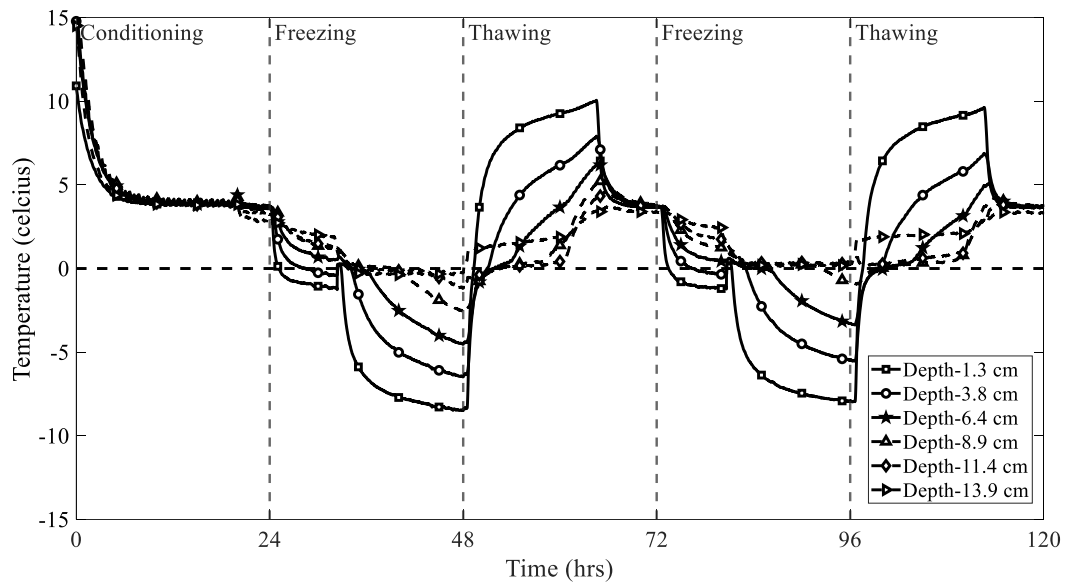


Figure 2. 10 Temperature profile of the IA-PC specimen

2.6 Water Intake

Pressure transducers were connected to Mariotte Water Supply for monitoring the water intake during frost heave testing. The Mariotte water supply was filled with water at the beginning of the test. As anticipated, the IA-PC soil specimen exhibited a high level of water intake during

the freezing process (Figure 2.11). This is attributed to the formation of an ice lens and subsequent ice segregation, which occurs as water migrates from the unfrozen zone to the frozen fringe zone. During the first thawing cycle, water intake decreased before sharply increasing once again during the second freezing cycle. Subsequently, water intake remained stable throughout the second thawing cycle.

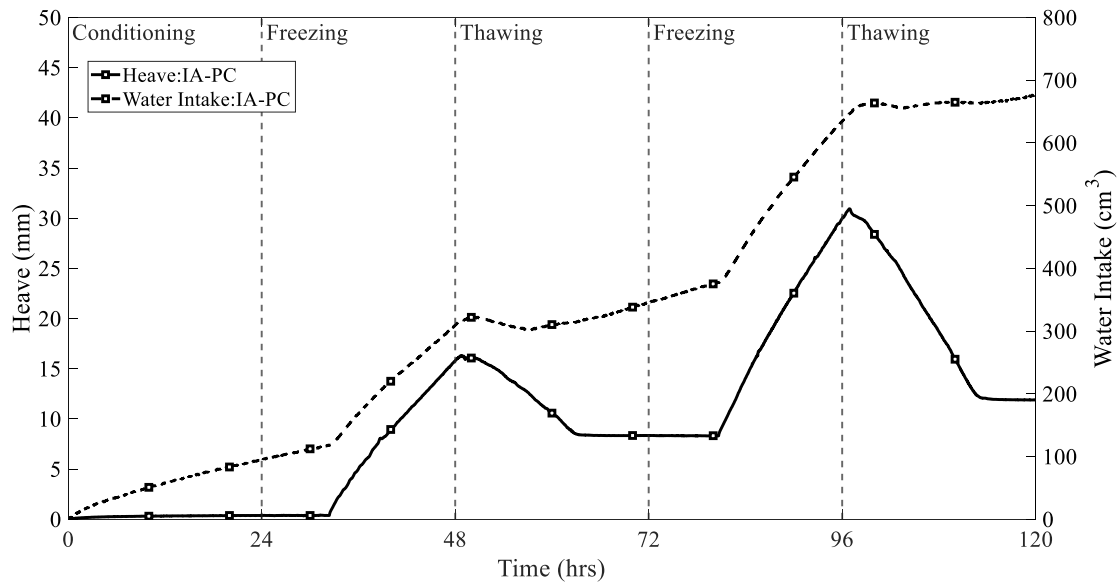


Figure 2. 11 Heave and water intake of the IA-PC specimen

2.7 Conclusions

Frost heave testing of four soils from different regions in Iowa was conducted to determine their frost susceptibility. The results showed that the amount of silt in soils significantly affected the frost susceptibility of soils. The soils with high silt content showed a higher amount of frost heaving. The maximum frost heave (30.9 mm) and heave rate (26.3 mm/day) were observed for IA-PC soil due to its high silt contents, followed by IA-BV. The IA-CC was least frost susceptible than the other three soils, possibly due to its low silt content providing low hydraulic conductivity and capillarity for this soil. The low hydraulic conductivity and capillarity limit the water migration to the frozen fringe zone, thus causing low heaving. The water intake was determined to be maximum during the freezing cycle because of water migration towards the frozen fringe due to ice lens formation.

2.8 Acknowledgment

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CHAPTER 3: FROST HEAVE EVALUATION OF SANDY AND CLAY SOILS UNDER OPEN AND CLOSED SYSTEMS WITH MULTIPLE FREEZE-THAW CYCLES

3.1 Abstract

Frost action in soils has a significant effect on the performance of roadways. This effect is more pronounced in the regions that are experiencing seasonal subfreezing temperatures as the soil undergoes multiple freeze-thaw cycles. Apart from the subfreezing temperature, the frost action is also affected by the soil type, as the void ratio and hydraulic conductivity of soils control the presence and movement of water for the growth of ice lenses. Frost heave is mainly attributed to silty soils, but significant frost heave can also occur in clay and sandy soils under favorable environmental conditions. For the present study, frost heave and thaw settlement of clayey and sandy soils, subjected to a one-dimensional freeze-thaw cycle, is investigated to determine how the frost action varies with soil types. Soil specimens were subjected to ten freeze-thaw cycles. Total heaving, heave rate, and water intake were measured as a function of time during testing. The moisture content of the soils after ten freeze-thaw cycles was also measured. The amount of pore water and external water supply affects the total heave during freeze-thaw cycles. Therefore, the effect of moisture availability during the freeze-thaw cycles was also investigated by comparing the results of specimens with or without an external water supply. Results of the study suggested that significant frost heave occurred in both clay and sandy soils. In addition, the application of ten freeze-thaw cycles provided a better estimation of the total heave than that observed with two freeze-thaw cycles (typical/standard numbers of freeze-thaw cycles). The maximum heave (40.9 mm) and heave rate (5.01 mm/day) were found to be higher in clay soil. The presence of an external water supply contributed to the frost action, and total heave was seven times higher in soils with an external water source. Soil with a free water supply showed 1.1-1.7 times higher moisture content after ten cycles compared to the soils with no external water supply. These results can be used in estimating the frost heave potential of soils in different environmental conditions.

3.2 Introduction

The frost action in soils causes a significant challenge for the design, construction, and maintenance of geosstructural systems, such as pavement. The formation of ice lenses in soils can

cause considerable heaving followed by a substantial strength reduction during thawing which may lead to a systematic failure of the infrastructure. The annual cost of mitigating damages caused by freeze-thaw (F-T) through current strategies is estimated to exceed \$2 billion (FHWA, 1999). For the frost action in soils, three requirements are (1) frost susceptible soils, (2) freezing temperature, and (3) free access to water (Chamberlain, 1981; Penner, 1959). The extent of damage caused by the F-T depends on the previous three factors.

It is accepted that some soils are more prone to frost heave action than others and are known as frost susceptible soils. However, any soil can show frost heave if favorable conditions are met (Bai et al., 2018; Naqvi et al., 2022; Sheng, 2021). The frost action in the soil depends upon the soil's suction and permeability (Carter & Bentley, 2016). Clay soils have suction but very low permeability, while sandy soils have high permeability but negligible suction and water retention capacity. Therefore, intermediate particle-size soils such as silts are most susceptible to frost. Soils in regions with seasonal freezing temperatures undergo multiple F-T cycles causing failures in the infrastructure (Cetin et al., 2019). Studies have shown that geotechnical properties of soils such as void ratio, porosity, permeability, plastic limit, consolidation, resilient modulus, and shear strength are significantly affected by the number of F-T cycles (Cui et al., 2014; Kumar & Soni, 2018; Qi et al., 2006; Rosa et al., 2016b; Swan et al., 2013). The ice formation in soils during freezing is due to the conversion of in situ pore water and migrated water from an external source into ice. Studies have shown that in situ pore water can only cause limited frost heaving due to limited water availability, but when the water is freely available, frost heave is significantly high (Hermansson & Spencer Guthrie, 2005). The migration of moisture toward the ice lens during freezing action is essential for continuous ice growth (Dagli et al., 2018; Taber, 1930). In situ pore water contributes to heaving at the beginning of freezing, while the external migrated water is the main contributor once the freezing front is ready (M. Zhang, Zhang, Xu, et al., 2017). The moisture content of the soil increases from the initial moisture content after F-T cycles (Y. Zhang et al., 2016).

The present study aims to study the three governing factors (soil type, F-T cycles, water) for frost actions. Two soil types, clay, and sand, are subjected to a one-dimensional F-T test. To understand the extent of F-T action, the soils are exposed to multiple F-T cycles. The effect of moisture on the frost action is studied by testing soils with (open system) and without water supply

(closed system). Frost heave was measured to determine the heave rate and maximum heave in soils subjected to multiple F-T cycles. In addition, the open system's water intake was monitored. It was also assessed how much the moisture content within the specimen's top to bottom had changed during testing.

3.3 Materials and Methods

The selected two soils are low plasticity clay collected from Pottawattamie County, Iowa (IA-PC) and silty sand collected from Boone County, North Carolina (NC-BO). These soils exist in different climatic regions in the USA and are exposed to freeze-thaw conditions under different environmental conditions. IA-PC experiences a wet, hard-freeze spring thaw in the field while the NC-BO experiences a wet, F-T cycling condition. Table 3.1 summarizes the index properties of both soils. The IA-PC and NC-BO are classified as CL and SM/SC. The grain size distribution curves of both soils are shown in Figure 3.1. Both soils contain a high percentage of silt content and are therefore expected to exhibit adequate frost susceptibility; however, the soils are primarily classified as clayey and sandy soils based on their index properties. Figure 3.1 shows that the fine contents of IA-PC soil are higher than that of the NC-BO soil. Both soils exist in F3 groups based on the frost susceptibility classification by the U.S. Army Corps of Engineers (1965) (Table 3.1), and this indicates that both soils are frost susceptible (ranging from low to very high).

The frost heave testing of soil specimens was conducted using freezing-thawing test equipment, as shown in Figure 3.2 (per ASTM D5918). Two specimens of each soil type were prepared. One specimen was subjected to a free external water supply (open system), while the other sample was not subjected to any external water supply (closed system). To prepare the specimens, the oven-dried soils were first crushed and passed through a 4 mm sieve. The cylindrical samples were compacted with 33 blows in 6 layers using a standard proctor hammer. The specimens were compacted at their optimum moisture content (OMC) (Table 3.1) and maximum dry density. The specimen sizes were 14.6 cm in diameter and 15.2 cm in height. The specimens were compacted within a latex membrane (to avoid leaks after inserting thermocouples during testing) and six acrylic rings of 2.54 cm height to restrain the sample laterally. After compaction, the specimens were placed over a base plate that was connected to a Mariot cylinder to act as a water source for the open system. The base plate was not connected to the water supply for specimens with a closed system. All the specimens were saturated for 24 hours.

Table 3. 1 Summary of soil index properties and classifications of IA-PC and NC-BO soils

Soil Properties	IA-PC	NC-BO
Specific Gravity, G_s (ASTM D854-14)	2.80	2.67
Liquid Limit, LL (%) (ASTM D4318-17)	37	38
Plasticity Index, PI (%) (ASTM D4318-17)	13	NP
Silt content (%) ($75\ \mu\text{m}$ – $2\ \mu\text{m}$)	86.2	34.0
Clay content (%) ($< 2\ \mu\text{m}$)	12.0	4.6
Optimum Moisture Content (%) (ASTM D698-12)	17.3	15.6
Max. Dry Unit Weight (kN/m^3) (ASTM D698-12)	16.7	16.9
Saturated Hydraulic Conductivity (cm/s)	$5.02\text{e-}08$	$6.34\text{e-}06$
USCS Classification	CL	SM/SC
AASHTO Classification	A-6	A-4
Frost Susceptibility Group ⁺	F3	F3

*N.P.- Non-Plastic

⁺Frost susceptibility classification by U.S. Army Corps of Engineers (1965) based on grain size distribution.

F1-Low frost susceptibility; F4-Very high frost susceptibility

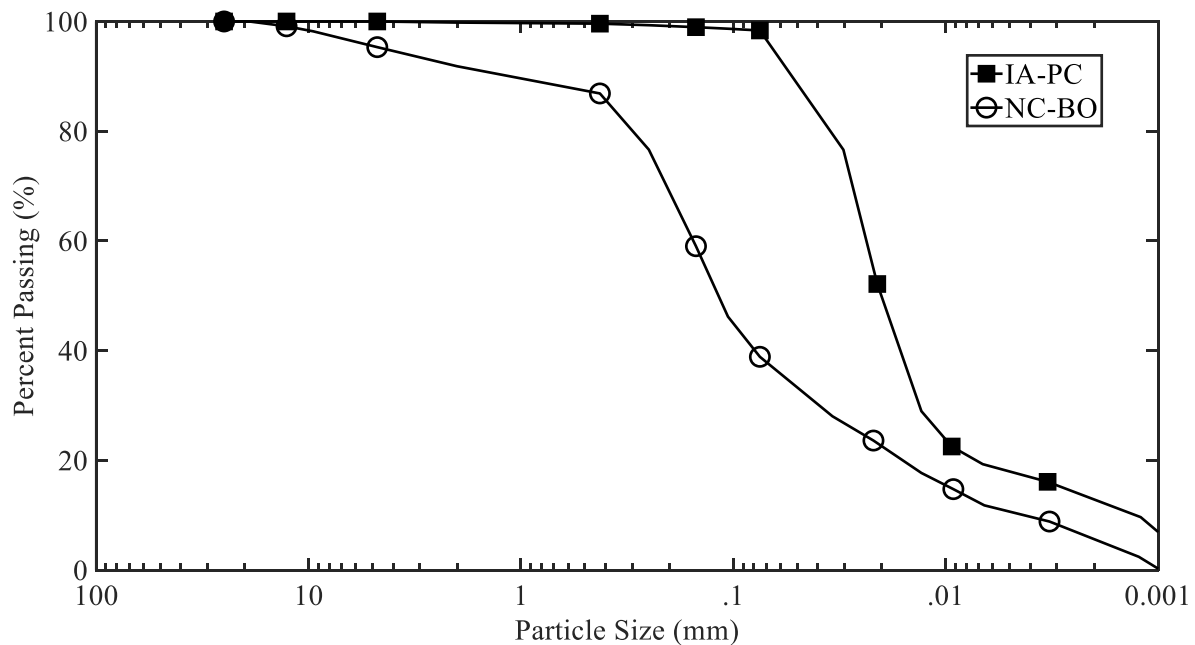


Figure 3. 1 Grain size distribution of soils (ASTM D6913)

of the Marriot bottle was 7.62 cm. Thus, every unit cm water intake means 7.07 cm³ in volume. The temperature of the specimen during experiments was measured with 8 T-type thermocouples placed vertically at every 2.5 cm. The freezer was filled with packing peanuts, and all the hoses were thermally insulated to minimize any heat loss and avoid any external effects. The specimens were subjected to 24-hour conditioning followed by 10 F-T cycles leading to a total test duration of 21 days. The temperature program adopted for testing was similar to the ASTM method as shown in Figure 3.3, except the F-T cycles were extended from two to ten. After the experiment, the specimens were disassembled and sliced into six pieces to determine the gravimetric moisture content of the specimens from top to bottom.

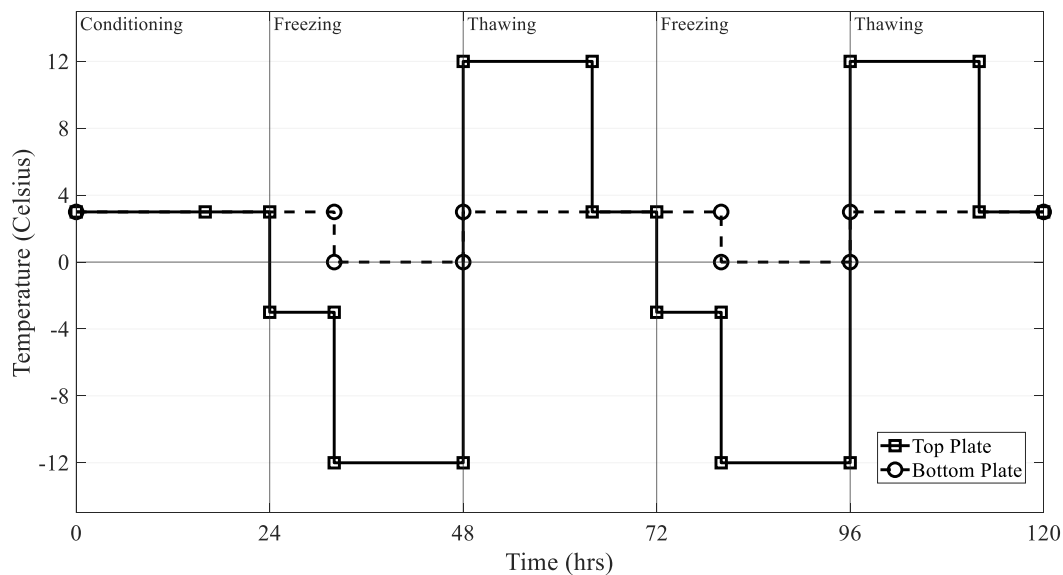


Figure 3. 3 Temperature in circulating bath for top and bottom heat exchange plates.

3.4 Results and Discussion

Total Heaving, Heave Ratio

Figure 3.4 presents the frost heave and thaw settlements of the soil specimens under ten F-T cycles. The solid line represents the specimen with an open system, while the dashed line shows the heave of the specimens tested with a closed system. No heaving was observed during the first 24 hours (conditioning period) as the temperature was above freezing temperature. All soils showed heaving during freezing and settlement during thawing cycles, as expected. For an open system, it is evident that the specimens heave higher with an increase in the number of F-T cycles.

On the other hand, for a closed system, the magnitude of heave did not change with the number of F-T cycles. This occurs because the water available in the soil for the closed system is limited; thus, its conversion to ice lenses during freezing temperatures is minimal. In addition, the absorbed and adsorbed water doesn't convert into ice as per frozen fringe theory. Therefore, the heave in soil with a closed system is expected to be lower and the heave stabilizes from the first cycle for both soils in a closed system. The maximum heave of the closed system specimens was significantly lower (5.73 mm for IA-PC) compared to those observed for the open system (40.91 mm for IA-PC).

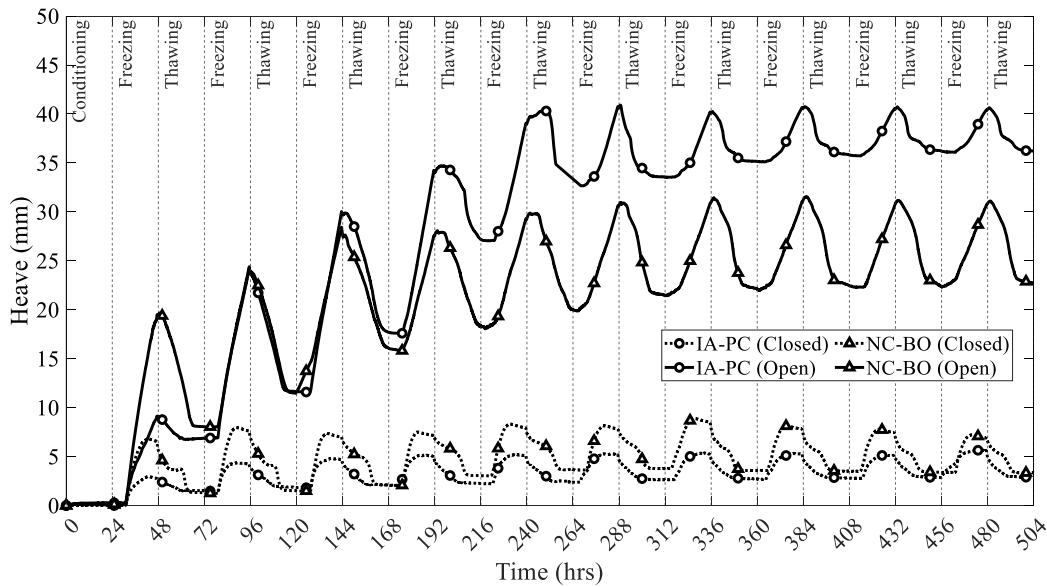


Figure 3. 4 Heave and thaw of different soils during frost heave testing

For soils with the open system, the heave was considerably higher compared to the closed system. This is due to the water migration induced by the temperature gradient (Xu et al. 1999). A temperature gradient in the frozen soil means the development of water flux in the direction of decreasing temperature, which depends on the permeability of the frozen soil and the suction force of the force fringe (Perfect & Williams, 1980). Since the water was freely available, the specimens took external water that yielded large ice formations leading to a greater magnitude of heaving (40.91 for IA-PC). This is also evident from the water intake during the experiment, as discussed in the later section. The maximum heave was observed in the first F-T cycle for NC-BO (open), which then reduced and stabilized at the 6th F-T cycle. A similar trend was observed for IA-PC (open) where the heaving stabilized at the 6th cycle. However, for IA-PC (open), the maximum

heave was observed in the second F-T cycle. This is caused by the lower initial hydraulic conductivity of IA-PC (Table 3.1) due to high clay contents in IA-PC. After the first F-T cycle, the formation of large voids as well micro fissuring may have led to an increase in the hydraulic conductivity of IA-PC soil, causing a significant amount of heaving during the second F-T cycle. Then, similar to NC-BO, the magnitude of heave decreased and stabilized at the 6th F-T cycle. The total heave of IA-PC in the open (40.91 mm) was higher than that of NC-BO (31.54 mm). This is because IA-PC soil had higher silt content compared to NC-BO soil. As silt contributes to the heaving process the most, the total heave in IA-PC soil was determined to be higher than that of NC-BO soil.

The total heaving during the experiment after two and ten F-T cycles is shown in Figure 3.5. Current testing standards suggest testing two F-T cycles. However, soils, in general, especially in harsher climatic regions, are subjected to higher F-T cycles per year which may have a high impact on the frost-heave behavior of soils. Figure 3.5 clearly shows this effect where the soils subjected to 10 F-T cycles experienced up to 1.7 times higher frost heave amount than those subjected to 2 F-T cycles. The heaving of both soils stabilizes after the 6th F-T cycle. These results show that two F-T cycles may not be enough to assess the frost heave potential of soil, and more F-T cycles may provide better insight into soil behavior during F-T conditions.

The Frost heave ratio (ξ) is defined as the proportion of the frost heave increment (Δh) up to frost depth (H_f) over a certain period of time (equation 1). The frost depth in the soil is the depth at which the freezing temperature is present, and ice formation can occur. For the current experiment, the temperature data from the thermocouple at the bottom of the specimen shows that the freezing temperature was present at the bottom of the specimen. Therefore, frost depth is considered as the height of the specimen in the present case, and total heave after the 10th F-T cycle is considered to calculate the frost heave increment. The frost heave ratio of the specimens is shown in Figure 3.6. IA-PC in an open system showed the maximum frost heave ratio (23.8 %), followed by NC-BO (14.6) in an open system. On the other hand, the frost heave ratio for the soils with the closed system was 1.9% and 2.2% for IA-PC and NC-BO, respectively.

$$\xi = \frac{\Delta h}{H_f} * 100\% \quad \dots\dots\dots(3.1)$$

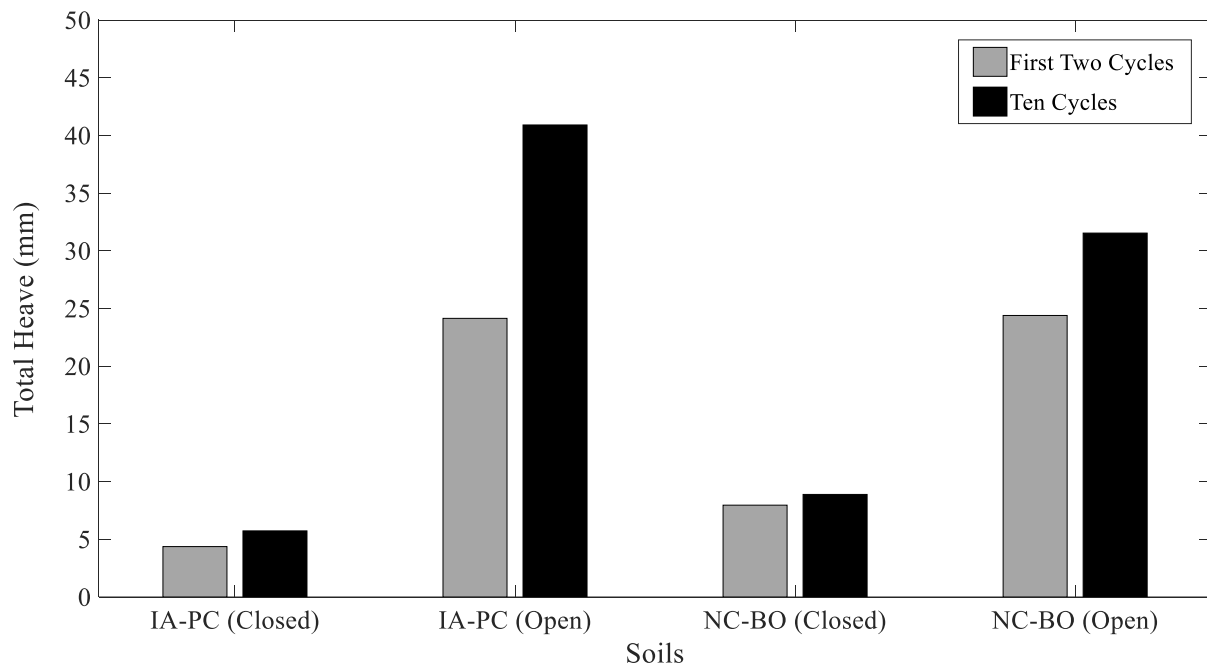


Figure 3. 5 Total Heave after two and ten F-T cycles

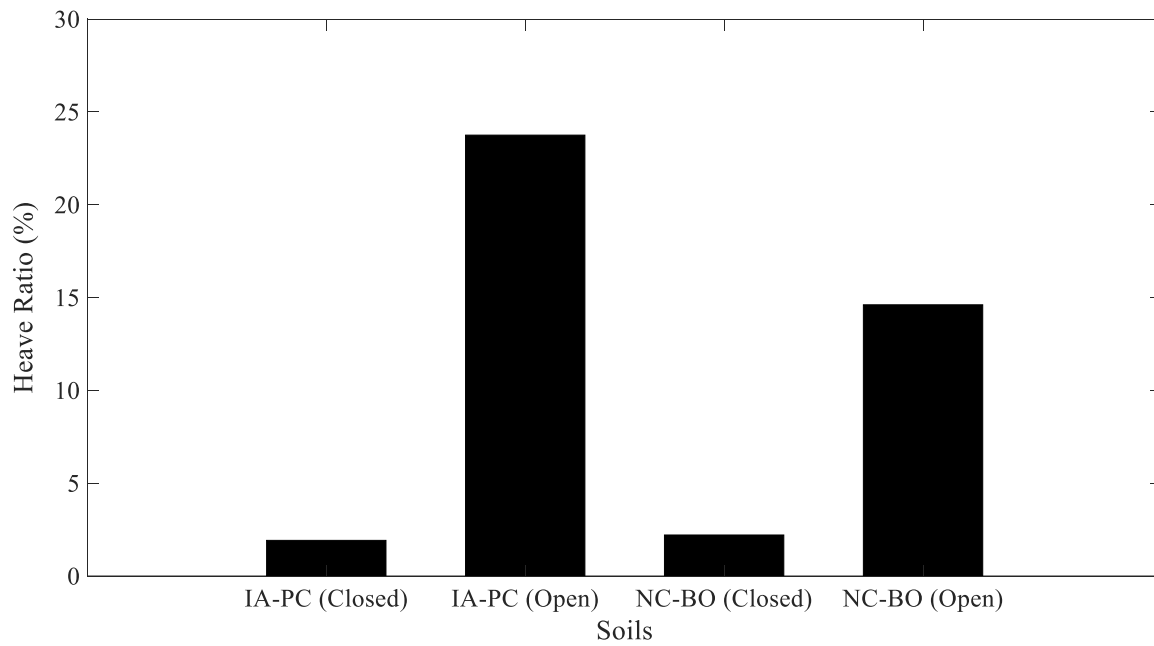


Figure 3. 6 Frost Heave ratio

Water Intake

Figure 3.7 shows the water intake by soils during the frost heave experiments along with the corresponding heave data at the open system. The results corroborated with the frost heave data. The general trend shows that more water enters the soils during freezing relative to thawing because of the water flux toward specimens due to temperature gradient. This suggests that the major contribution to heaving is due to external moisture sources. Excess water in fully saturated soil retracts back into the Marriot bottle during thawing periods at a few thawing cycles. The amount of water intake by sandy soil (NC-BO) was higher in the initial F-T cycles than in the clayey soil (IA-PC). Similar to the heave data, the water intake also stabilized after the 6th F-T cycle, and only limited water entered the specimens during the remaining F-T cycles. The total water taken by the soils after 10 F-T cycles was similar.

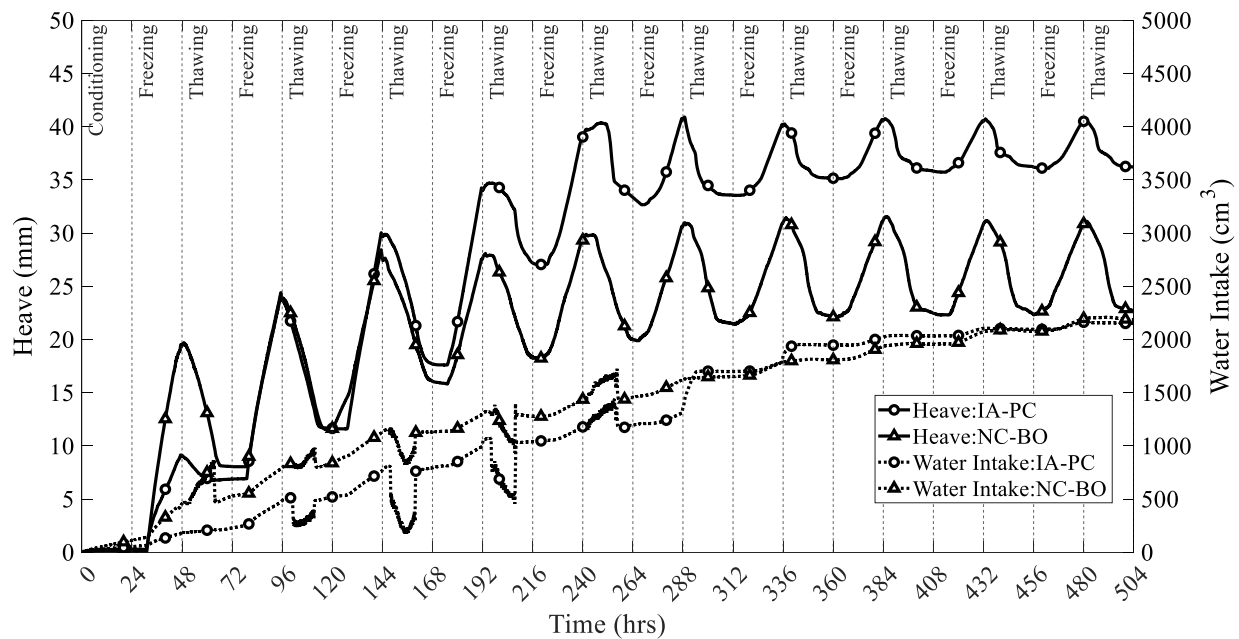


Figure 3. 7 Water intake by soils during frost heave testing

The moisture content of the specimens with depth after the F-T test is shown in Figure 3.8. The moisture content of soils increased considerably from the initial optimum moisture content, especially for the soils with open systems. The moisture contents of soils with an open system were significantly higher than the ones with a closed system. It is worth noting that the moisture content of the closed system specimen is higher than its OMC because of the saturation that is applied before the frost heave test, and the specimen primarily undergoes moisture redistribution

during the test. Since the freezing starts from the top, the moisture content increases towards the top of the specimens due to the migration of the water toward the frozen fringe. Therefore, the differences in the moisture contents between the bottom and top of IA-PC soil were 3.1% and 13.8% for a closed and open system, respectively. Similarly, this difference for NC-BO soil was 6.8% and 10.7%, respectively.

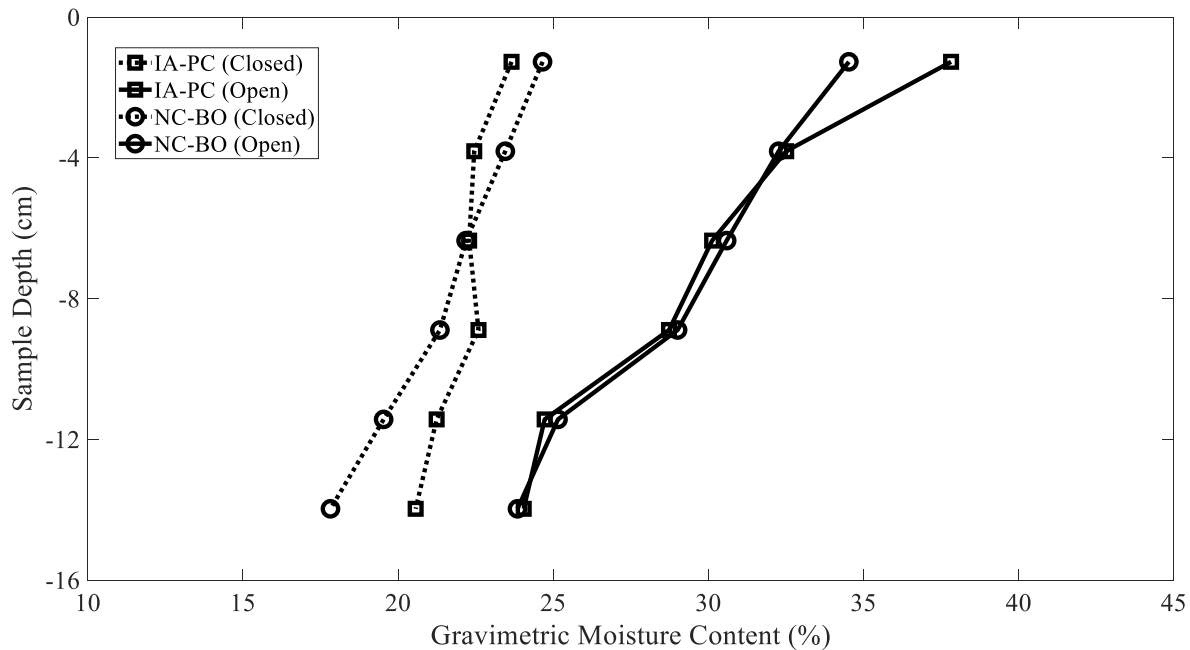


Figure 3. 8 Gravimetric moisture contents of soils after frost heave testing

Temperature Profile

The temperature distributions of IA-PC soil specimens for the closed and open systems are illustrated in Figure 3.9. The minimum temperature at a depth of 11.4 cm is 1.9°C lower in the closed system compared to the open system; thus, the frost penetration rate is higher in the closed system. The frost penetration rate and depth depend on the thermal properties and moisture content of the soil. The thermal properties of both soil specimens in the closed and open systems are similar; therefore, the moisture content of the soil plays a crucial role in determining the frost penetration rate and depth. The amount of water in the soil significantly influences frost penetration, as more heat units (Btu) are required to freeze water compared to soil grains. In the open system, the continuous movement of water results in higher moisture content, and as a result,

more heat is needed to freeze the soil specimen. Consequently, the frost penetration rate is slower in the open system compared to the closed system.

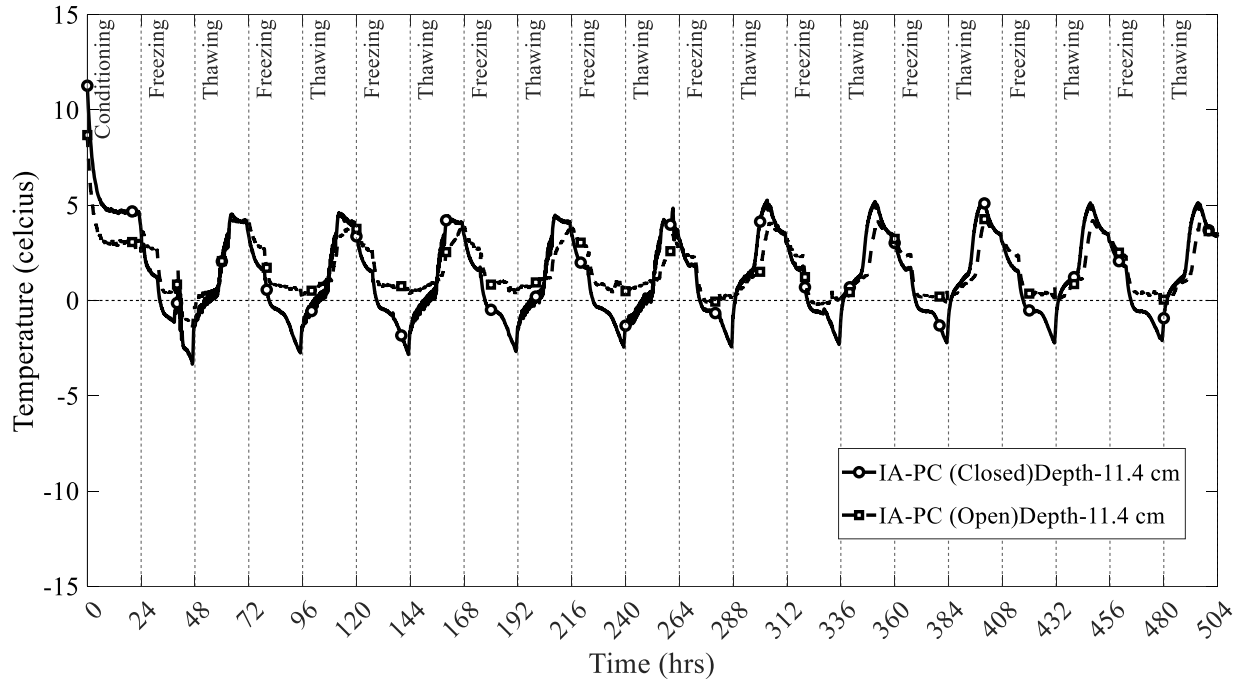


Figure 3. 9 Temperature profile of the IA-PC specimens at a depth of 11.4 cm

The temperature distribution of IA-PC and NC-BO specimens for a closed system at two different depths is shown in Figure 3.10. The freezing front penetrated both specimens at a depth of 11.4 cm from the top. However, IA-PC specimens displayed a lower temperature, indicating a higher rate of frost penetration. Soil's thermal properties significantly influence the heat distribution and temperature changes within the soil matrix, leading to differences in temperature propagation inside soil specimens. Chapter 4 discusses in detail the distinct behavior of IA-PC specimens in terms of temperature propagation.

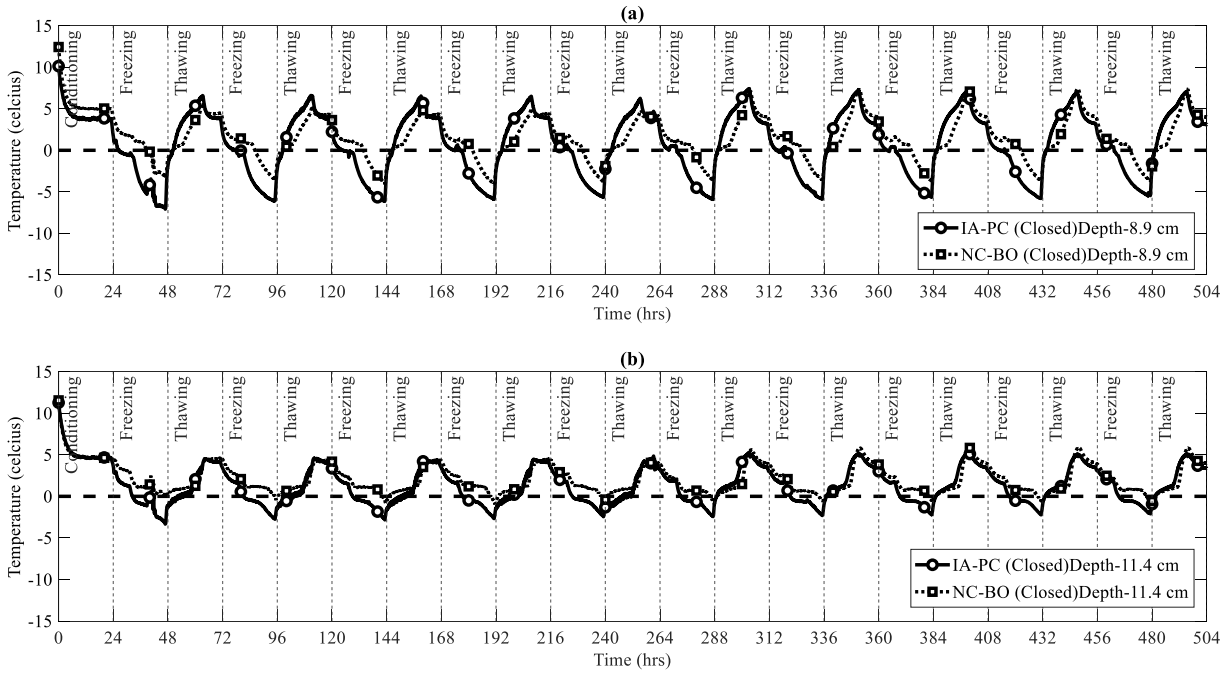


Figure 3. 10 Temperature profile of the IA-PC and NC-BO specimens at the depths of: (a) 8.9 cm; (b) 11.4 cm

3.5 Conclusions

Frost heave testing on sandy and clay soils was conducted. The long-term effects of F-T cycles were investigated by applying 10 F-T cycles on the soils with (open system) and without water supply (closed system). The heave was consistent after the first F-T cycle for both soils when no water supply was provided. For soils with water supply (like shallow ground water table), that maximum heave was observed in the first F-T cycle for sandy soil due to high permeability, while the maximum heave for clayey soil was observed during the second freezing cycle due to the development of large voids and micro fissuring after the first F-T cycle causing a significant increase in the permeability of IA-PC soil. The heave of both specimens continuously increased up to the 6th F-T cycle and then stabilized. The total heave of IA-PC in the open system was 7 times higher than that of the closed system. Higher heave ratios of 23.75% and 14.61% were found in the open system for IA-PC and NC-BO, respectively. The differences in total heave after the second and the tenth cycle were significant for soil tested with an external water supply. Therefore, multiple F-T cycles should be applied to better estimate the heave potential of the soils. The water intake data during F-T cycles followed the heaving trends. The moisture contents of the soils after

ten F-T cycles differed noticeably between the open and closed systems, and the open system soils showed considerable increases in moisture content above their original optimal moisture contents. The water movement towards the frozen fringe caused the specimens' moisture levels to rise from the bottom to the top. This study will contribute to the database of frost heave behavior of various soil types and assist in assessing the extent of frost damage to pavements in various soil types subjected to different climatic conditions and moisture availability.

3.6 Acknowledgment

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CHAPTER 4: THE ROLE OF TEMPERATURE GRADIENT AND SOIL THERMAL PROPERTIES ON FROST HEAVE

4.1 Abstract

In cold regions, the soil temperature gradient and depth of frost penetration can significantly impact roadway performance due to frost heave and thaw settlement of the subgrade soils. The severity of the damage depends on the soil index properties, temperature, and availability of water. While nominal expansion occurs with the phase change from pore water to ice, heaving is derived primarily from a continuous water flow from the vadose zone to growing ice lenses. The temperature gradient within the soil influences water migration towards the freezing front, where ice nucleates, coalesces into lenses, and grows. This study evaluates the frost heave potential of frost-susceptible soils from Iowa (IA-PC) and North Carolina (NC-BO) under different temperature gradients. One-dimensional frost heave tests were conducted with a free water supply under three different temperature gradients of $0.26^{\circ}\text{C}/\text{cm}$, $0.52^{\circ}\text{C}/\text{cm}$, and $0.78^{\circ}\text{C}/\text{cm}$. Time-dependent measurements of frost penetration, water intake, and frost heave were carried out. Results of the study suggested that frost heave and water intake are functions of the temperature gradient within the soil. A lower temperature gradient of $0.26^{\circ}\text{C}/\text{cm}$ leads to the maximum total heave of 18.28 mm (IA-PC) and 38.27 mm (NC-BO) for extended periods of freezing. Maximum frost penetration rate of 16.47 mm/hour was observed for a higher temperature gradient of $0.78^{\circ}\text{C}/\text{cm}$ and soil with higher thermal diffusivity of $0.684\text{ mm}^2/\text{s}$. The results of this study can be used to validate numerical models and develop engineered solutions that prevent frost damage.

4.2 Introduction

In cold regions, repeated cycles of freezing and thawing (i.e., frost action) cause damage to transportation infrastructure, including pavements and granular roadways (Andersland and Ladanyi 2004; Li et al. 2014; Zhang et al. 2016). During the freezing cycle, osmotic and matric suction increases at the leading edge of frost penetration, and a hydraulic gradient is created. Water migrates from the unfrozen region to the frozen fringe, where it coalesces with previously formed ice in the pore space or as discrete lenses. The migrated water causes the majority of overall frost heave deformation. The rate at which this water migrates is a function of the prevailing hydraulic gradient, temperature gradient, and hydraulic conductivity.

The primary factors governing water movement during freezing are temperature gradient, soil type, water potential, and unfrozen water content (Bing et al., 2015). Some water typically remains unfrozen in soils below the freezing point of water due to the capillarity and surface energy of soil particles (Dash et al., 1995). The unfrozen water content influences the soil's thermal and mechanical properties, which dictate the soil's water migration and frost heave (Li, Chen, and Sugimoto 2020). Water migration and frost heave processes have been studied under different scenarios in the past (Zhang et al. 2018; Naqvi et al. 2022; Loch and Kay 1978; Lai et al. 2014). Naqvi et al. (2022) investigated the frost action of soils from different climatic regions and observed that soils with high silt and low clay content experienced the maximum frost heave. Zhang et al. (2018) developed a model to predict the distribution of water content across the depth of the soil, as well as variations in water content with temperature in the unfrozen zone, frozen fringe, and frozen region. Loch and Kay (1978) studied the water flux under different temperature gradients by freezing the specimen from the bottom and allowing access to water at both the top and bottom of the specimen. In the field, freezing usually occurs from the top downward and water migrates mostly from the unfrozen zone to the frozen zone which is typically from bottom up. Lai et al. (2014) observed that the frost heave of saturated soil with a no-pressure water supply was greatly influenced by temperature gradients, overburden pressures, and cooling temperatures. Zhang et al. (2017) observed the deformation in soil by applying different temperature gradients to silty clay soil. The maximum freezing temperature of -4°C was used, and the heat was supplied from both the top and bottom of the specimen. In the field, soil experiences much lower freezing temperatures. Moreover, a temperature boundary of -1°C and $+1^{\circ}\text{C}$ was used as the minimum temperature gradient. But several studies suggested the presence of unfrozen water at a temperature below -1°C and freezing point depression below 0°C for the soil-water system (Rosa et al. 2016; Li, Chen, and Sugimoto 2020; Zhang et al. 2022).

Several previous studies investigated the effect of temperature gradients by varying the temperatures at both the cold and warm ends. However, it is difficult to control the freezing temperature and temperature gradient when the top and bottom temperatures are independently altered, as the prevailing temperature regime, and therefore the amount of unfrozen water content will be different. Furthermore, higher freezing temperatures were used in comparison to the field in the previous studies (Lai et al. 2014; Zhang et al. 2017). Therefore, an experimental program was carried out to study the effect of freezing temperature variation and temperature gradients on

two different soils by applying a one-directional freezing condition with an external water supply. The cold end temperature at the top of the specimen was changed, while the bottom warm end temperature was kept constant. Frost heave tests were conducted at three different temperature gradients (0.26, 0.52, and 0.78 °C/cm), where 0.78 °C/cm is the ASTM D5918 (2013) suggested temperature gradient for the frost heave test. The advance rate of the freezing front was monitored with thermocouples under different temperatures. The soil's frost heave profile and water intake at different temperature gradients were studied during the experiment.

4.3 Materials

Silty sand from U.S. 221 near Boone, North Carolina (NC-BO) and low plasticity clay from Pottawattamie County, Iowa (IA-PC), respectively, were collected for the experimental program of this study. These soils are subjected to different freeze-thaw conditions. The United States was divided into four climatic regions by the Long-Term Pavement Performance (LTPP) program depending on annual precipitation and freezing index parameters (FHWA, 2015). Iowa has been classified as a Wet-Freeze (W.F.) region, and the North Carolina site location in the mountainous Western part of the state is classified as a Wet, Moderate Freeze region. The presence of high frost susceptible soil (silts) in this part and wet conditions can cause significant damage to the transportation infrastructure.

The grain size distribution of the soils was conducted following ASTM D6913 (ASTM International, 2014a) and presented in Figure 4.1. IA-PC and NC-BO soils have 86.2% and 34% silt contents, respectively, and clay contents of 12% and 4.6%. NC-BO soil has a substantially greater sand concentration of 56.4% compared to 1.6% for IA-PC soil. Table 4.1 summarizes the properties of both soils. According to the Unified Soil Classification System (USCS), IA-PC soil was classified as low-plasticity clays (CL), and NC-BO soil was classified as silty sand/clayey sand (SM/SC). NC-BO soil has a much higher hydraulic conductivity of 6.34×10^{-6} cm/s, compared to 5.02×10^{-8} cm/s for IA-PC. Thus, during frost action, water can flow considerably more easily through the pores of NC-BO soil than IA-PC soil. In addition, both soils fall within the F3 groups of the U.S. Army Corps of Engineers (1965) frost susceptibility classification, which implies that both soils are frost-susceptible (medium to high).

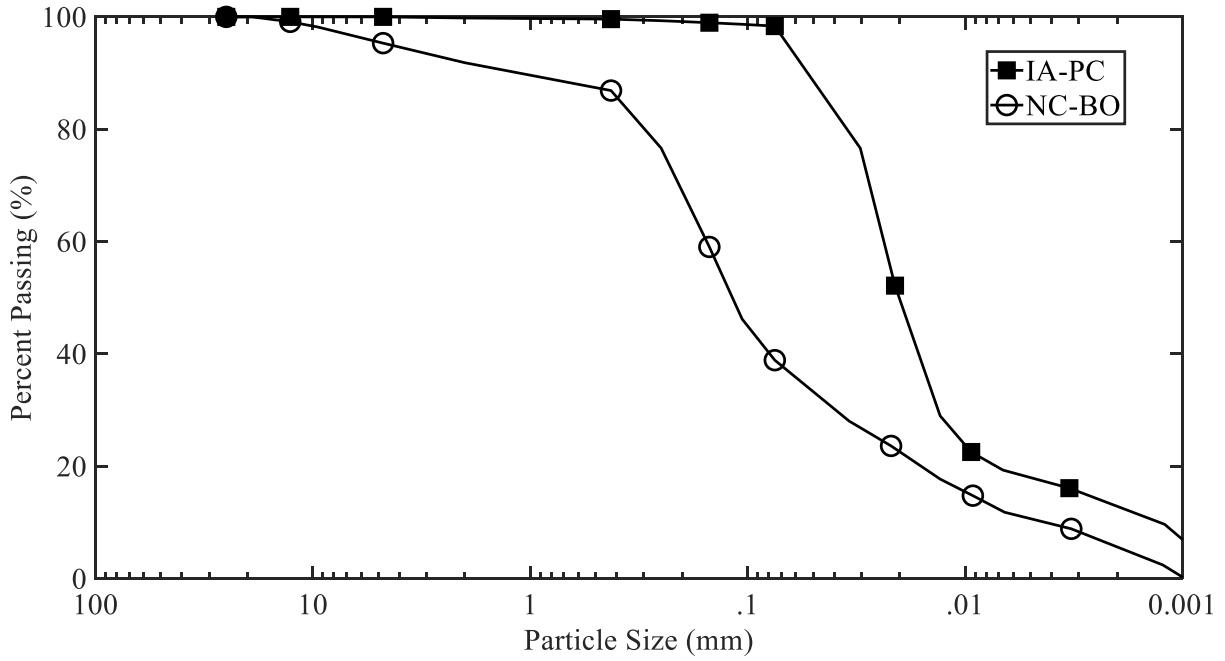


Figure 4. 1 Grain size distribution of the soils

4.4 Methods

One-directional freezing experiments were performed under different temperature gradients with a water supply to evaluate the effect of temperature variation on the frost-susceptible soils. The collected soil samples were dried in an oven, sieved through a U.S. No. 4 sieve, and uniformly mixed at the corresponding optimum moisture content. Each specimen was compacted in six layers with a laboratory-designed mold and a Proctor compaction hammer. After compacting each layer with 33 blows, the prepared specimens were saturated for 24 hours according to the pressure-head schedule specified in ASTM D5918(2013). Six acrylic rings and a latex membrane were placed around each specimen to provide lateral confinement. The dimensions of the specimens were 15.2 cm in height and 14.6 cm in diameter. The thermal properties of the soil specimens were measured using KD2 Pro (SH-1) after saturation.

The tests were carried out in a cooling chamber with a set temperature fixed at 4°C. To apply a freezing temperature, two heat exchanging plates were positioned at the top and bottom of each specimen. Table 4.2 shows the temperature gradient and freezing temperature conditions for both soil specimens. Each test was conducted for 144 hours with 24 hours of initial conditioning at 1°C and a freezing duration of 120 hours. In case 1, a lower temperature gradient of 0.26°C/cm

was applied with top and bottom plate temperatures of -4°C and 0°C , respectively. In case 2, a $0.52^{\circ}\text{C}/\text{cm}$ temperature gradient was applied with -8°C and 0°C top and bottom plate temperatures, respectively. The third case involved a temperature gradient of $0.78^{\circ}\text{C}/\text{cm}$, with the top plate temperature set to -12°C and the bottom plate to 0°C . Two different programmable temperature-control circulating baths were used to regulate the temperature of the specimens. The circulating baths have an operating temperature range of -30°C to $+200^{\circ}\text{C}$ and a temperature stability of $\pm 0.005^{\circ}\text{C}$.

In addition, to simulate a field situation in which there is access to water (e.g., a relatively high groundwater table), water was supplied at the bottom of the specimens by connecting the base plate with Mariotte bottles using flexible hoses and a constant pressure head of 1.27 cm was maintained. A separate Mariotte bottle was used for each specimen. A 5.5 kg (3.5 kPa) surcharge was applied to each specimen following ASTM D 5918 (2013) to replicate the weight of granular roadway materials/pavement structure layers above the subgrade.

During the test, frost heave was measured using laser-displacement transducers. The laser had a measurement range of 5 cm and a resolution of $0.75\text{ }\mu\text{m}$. Each specimen was equipped with eight thermocouples at depths of 0, 1.3, 3.8, 6.4, 8.9, 11.4, 14, and 15.2 cm to monitor temperature differences over the length of the specimens. Type T thermocouples were used with a measuring range of -250°C to $+350^{\circ}\text{C}$, error limit of 1°C or 0.75% of the reading (whichever is greater) for above 0°C and 1°C or 1.5% of the reading (whichever is greater) for below 0°C . During the experiment, a pressure transducer was mounted at the base of the Mariotte bottle to measure the volume of water entering the specimens. The Mariotte bottle's diameter was 7.62 cm, and each unit of water intake corresponds to 45.60 cm^3 in volume. The Campbell Scientific CR1000X, data collection system was used to record the displacement, temperature, and water intake at one-minute intervals. The test set up for frost heave testing following the ASTM D 5918 (2013) is depicted in Figure 4.2. To reduce heat loss and prevent any outside influences, the cooling chamber was filled with packing peanuts, and all hoses from circulating bath to the specimens were thermally insulated.

Table 4. 1 Physical properties of the soils

Soil Properties	IA-PC	NC-BO
Specific Gravity, G_s (ASTM D854-14)(ASTM International, 2014b)	2.80	2.67
Liquid Limit, LL (%) (ASTM D4318-17)(ASTM International, 2017b)	37	38
Plasticity Index, PI (%) (ASTM D4318-17)(ASTM International, 2017b)	13	NP
Silt content (%) ($75\ \mu\text{m}$ – $2\ \mu\text{m}$)	86.2	34.0
Clay content (%) ($< 2\ \mu\text{m}$)	12.0	4.6
Optimum Moisture Content (%) (ASTM D698-12)(ASTM International, 2012)	17.3	15.6
Max. Dry Unit Weight (kN/m^3) (ASTM D698-12)(ASTM International, 2012)	16.7	16.9
Saturated Hydraulic Conductivity (cm/s)	5.02×10^{-8}	6.34×10^{-6}
USCS Classification (ASTM D2847) (ASTM International, 2017a)	CL	SM/SC
AASHTO Classification(AASHTO M145-91, 2012)	A-6	A-4
Frost Susceptibility Group ⁺ (US Army Corps of Engineers, 1965)	F3	F3

*N.P.- Non-Plastic

⁺F1-Low frost susceptibility; F4-Very high frost susceptibility

Table 4. 2 Testing conditions of the soil specimens

Soil type	Case	Initial conditioning Temperature (°C)	Temperature Boundary(°C)		Temperature Gradient (°C/cm)	Freezing Time (Hours)
			Bottom	Top		
IA-PC	1	+1	0	-4	0.26	120
	2	+1	0	-8	0.52	120
	3	+1	0	-12	0.78	120
NC-BO	1	+1	0	-4	0.26	120
	2	+1	0	-8	0.52	120
	3	+1	0	-12	0.78	120

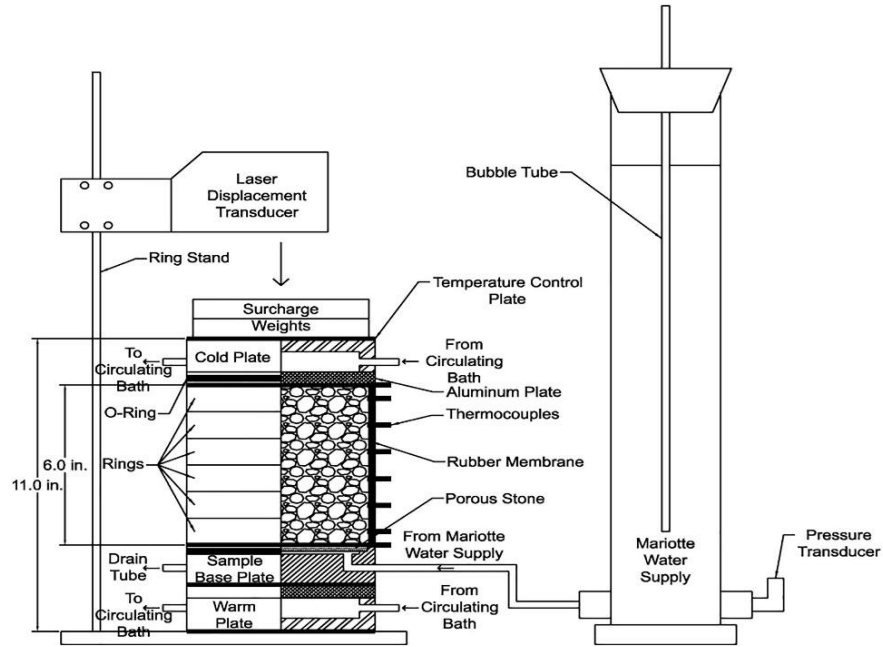


Figure 4. 2 Frost heave testing setup (Mahedi et al., 2020)

4.5 Results and Discussion

Temperature Distribution

The temperature distributions of IA-PC and NC-BO soil specimens for three different cases (Table 4.2) at various depths are shown in Figure 4.3 and Figure 4.4, respectively. The freezing front (0°C isotherm) propagated down to the bottom of the specimen for all three cases of IA-PC specimens. In contrast to IA-PC specimens (Figure 4.3), the freezing front moved much more slowly for NC-BO specimens (Figure 4.4) and could not penetrate 8.9 cm from the top in case 1 during the freezing duration. The time required for the freezing front to reach different depths based on the temperature distribution is given in Table 4.3. The 0°C isotherm propagated significantly faster in the specimens with a higher temperature gradient in both soils due to the lower freezing temperatures. In case 1, the zero-degree isotherm for the IA-PC specimen reached 1.3 cm from the top almost immediately (0.53 hours), whereas it took the NC-BO specimen 20.12 hours to reach the same depth. Similarly, in case 3, the frost penetrated at 14 cm from the top in 8.5 hours for the IA-PC specimen, but it took three times longer (30.35 hours) for the NC-BO specimen.

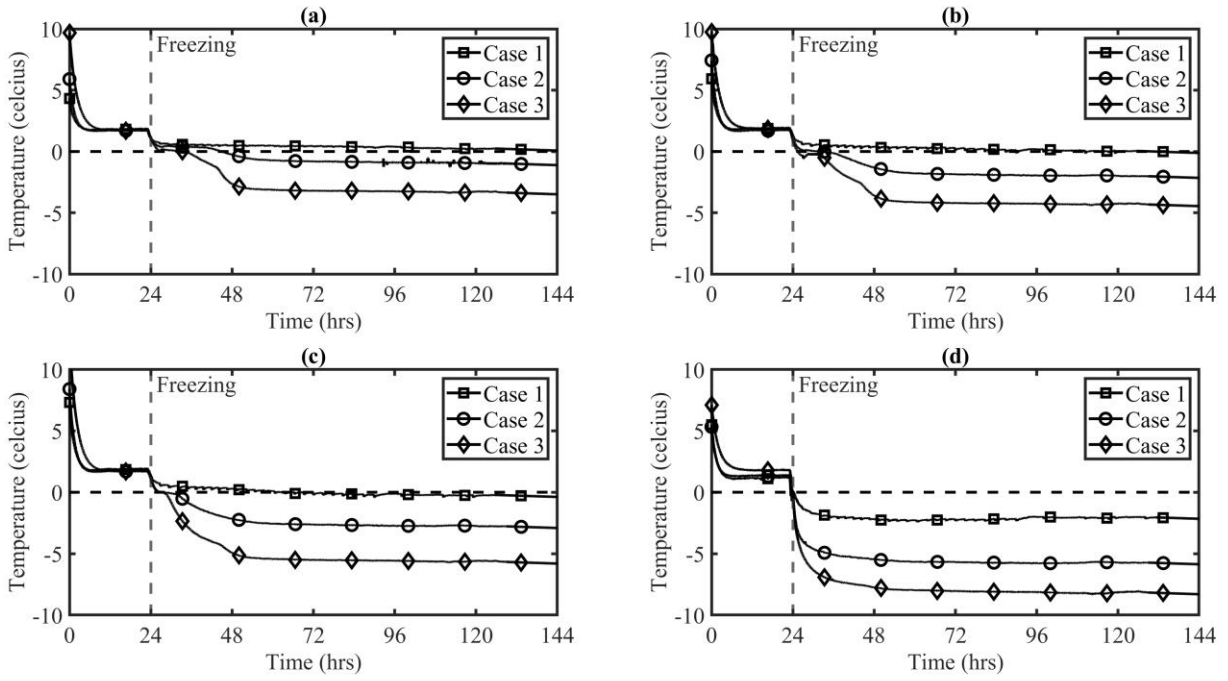


Figure 4. 3 Temperature profile of the IA-PC specimens at the depths of: (a) 14 cm; (b) 11.4 cm; (c) 8.9cm; (d) 1.3cm

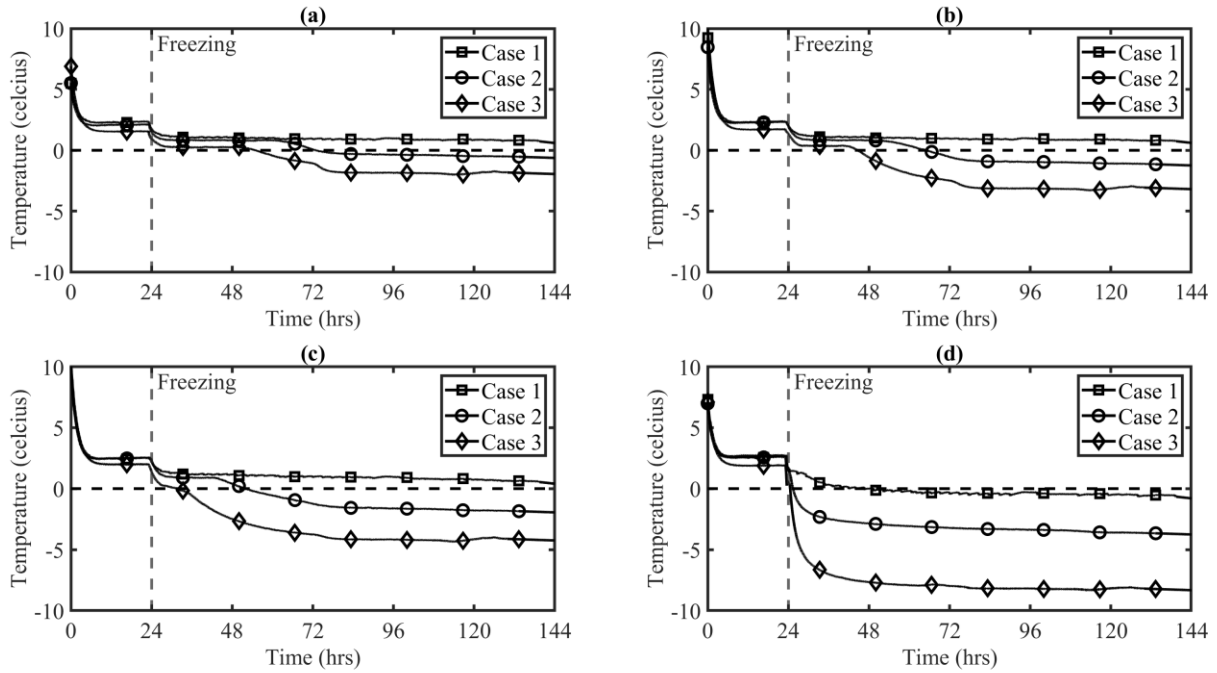


Figure 4. 4 Temperature profile of the NC-BO specimens at the depths of: (a) 14 cm; (b) 11.4 cm;(c) 8.9cm; (d) 1.3cm

Table 4. 3 Time needed for frost penetration at different depths.

Soil Type	Case	Temperature Gradient (°C/cm)	Depth- 1.3 cm	Depth- 8.9 cm	Depth- 11.4 cm	Depth- 14 cm
			Time needed (h)	Time needed (h)	Time needed (h)	Time needed (h)
IA-PC	1	0.26	0.53	39.31	82.8	118.32
	2	0.52	0.53	3	3.68	20.38
	3	0.78	0.53	2.11	2.56	8.5
NC-BO	1	0.26	20.12	-	-	-
	2	0.52	0.65	27.88	40.67	48.61
	3	0.78	0.65	6.24	21.61	30.35

Temperature propagation inside soil specimens behaves differently due to differences in the thermal properties of soil. Soil's thermal properties play a significant role in heat distribution and temperature changes within the soil matrix. The thermal properties of the specimens are shown in Table 4.4. The thermal conductivity, i.e., the ability to conduct heat, of both soils is nearly identical. But the specific heat of each soil is different from the others. Specific heat is the amount of heat needed/released to change the temperature of unit mass by 1°C. Since the specific heat of NC-BO specimens (2.69 MJ/ m³K) is higher than that of IA-PC specimens (2.29 MJ/m³K), more heat needs to be released to reduce the temperature of NC-BO. The temperature movement within the soil media depends on the soil's specific heat and thermal conductivity. Since temperature propagation depends on two different properties, thermal diffusivity has been introduced to simplify the explanation of temperature movement. Thermal diffusivity is a measure of how quickly a material reacts to temperature changes and is a function of specific heat and thermal conductivity (Speight, 2019). Thermal diffusivity can be expressed by **Equation 1** (Daniels et al., 2010; Fuchs et al., 2015).

$$\alpha = \frac{k}{\rho C_p} \quad (1)$$

where α is the thermal diffusivity, k is the thermal conductivity, ρ is density, and C_p is the specific heat.

A higher thermal diffusivity causes temperature change to occur more rapidly. Similar to thermal conductivity and specific heat, thermal diffusivity was measured using KD2 Pro (SH-1). The thermal diffusivity of the IA-PC specimen (0.68 mm²/s) is higher than that of the NC-BO specimen (0.59 mm²/s), so the frost front penetrated the IA-PC specimen more quickly. Figure 4.5

shows the frost penetration rate for both soils. As discussed, the frost penetration rate for IA-PC is much higher than NC-BO, and case 3 has the highest frost penetration rate for both specimens due to the higher freezing temperature. These results are consistent with the general trend of increasing heat loss with larger values of thermal diffusivity (Daniels et al., 2010). Increased heat loss corresponds to greater frost penetration although not necessarily greater ultimate heave, depending on the prevailing hydraulic conductivity and access to water.

Table 4. 4 Thermal Properties of the soil specimens

Properties	IA-PC	NC-BO
Thermal conductivity W/(mK)	1.57	1.59
Specific Heat M.J./ (m ³ .K)	2.29	2.69
Thermal diffusivity (mm ² /s)	0.68	0.59

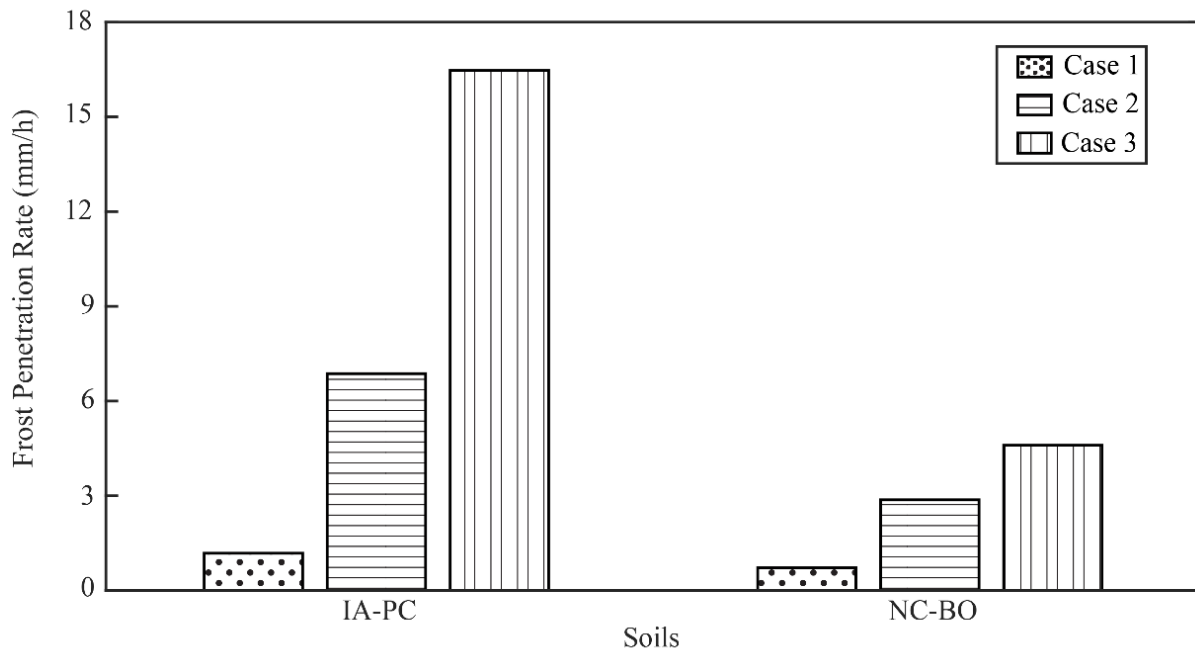


Figure 4. 5 Frost penetration rate of soil specimens during freezing process

Heave trends and water intake

Figure 4.6 and Figure 4.7 show the frost heave time plots and water intake for three cases of IA-PC and NC-BO soils, respectively. The soil specimens' heaving nature is directly related to the water intake amounts and frost penetration depths. The water flows into the soil specimen due to the cryogenic suction at the ice-water interface and the temperature gradient (Doré, 2004; Perfect & Williams, 1980). The temperature gradient in the frozen soil drives water flux in the

direction of decreasing temperature, and the volume of water intake depends on the permeability of the soil specimen and the cryogenic suction.

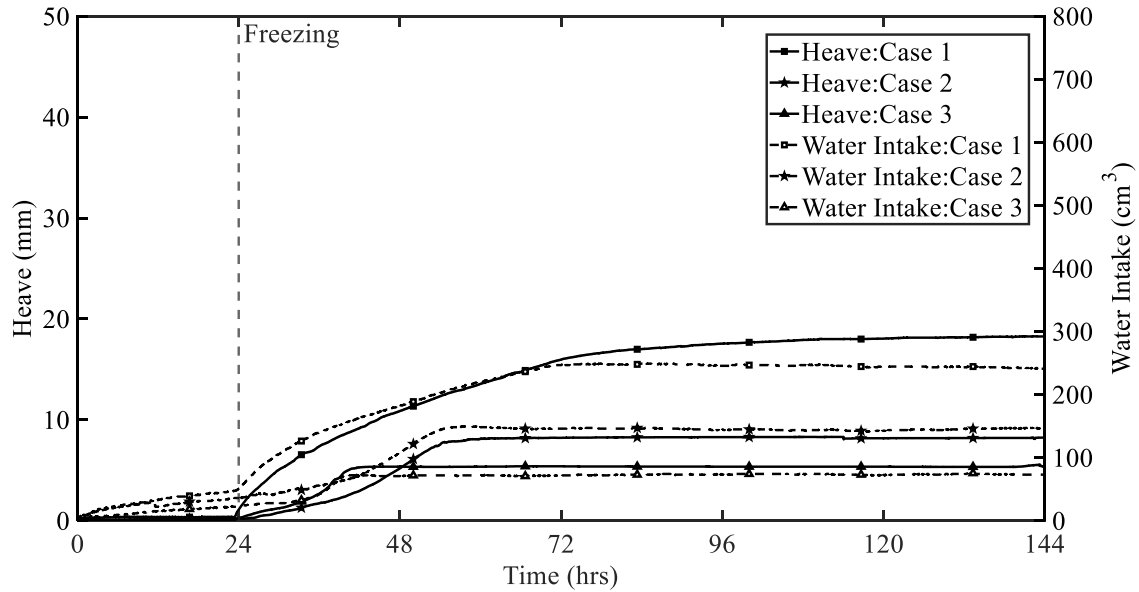


Figure 4. 6 Heave and water intake of the IA-PC specimens

For IA-PC (Figure 4.6), the zero-degree isotherm penetrated 14 cm of 15.2 specimen after 8.5 hours of freezing for case 3. Since frost penetrated the entire specimen, there was no more water intake after 15 hours of freezing (39 hours from the start of the test) due to a significant drop in the hydraulic conductivity of frozen soil. The additional time for water intake after 8.5 hours was due to frost penetration to the lower 1.2 cm and the presence of unfrozen water at 0°C in the frozen fringe region. In the frozen fringe, the temperature is slightly below the bulk freezing point of water, between approximately 0 to -2 °C, but no ice lenses are present (Tiedje, 2015). Since the ice lenses are not developed at that temperature, water can still migrate after penetration of the zero-degree isotherm. When the water movement ceased, the heaving of the samples likewise became stable. A similar phenomenon was observed in all three cases of both soils. Case 1, with the lowest temperature gradient, had the maximum heave (18.28 mm) for IA-PC since it took longer to freeze the entire sample, and water migration continued until the ice lenses developed at the bottom of the specimen.

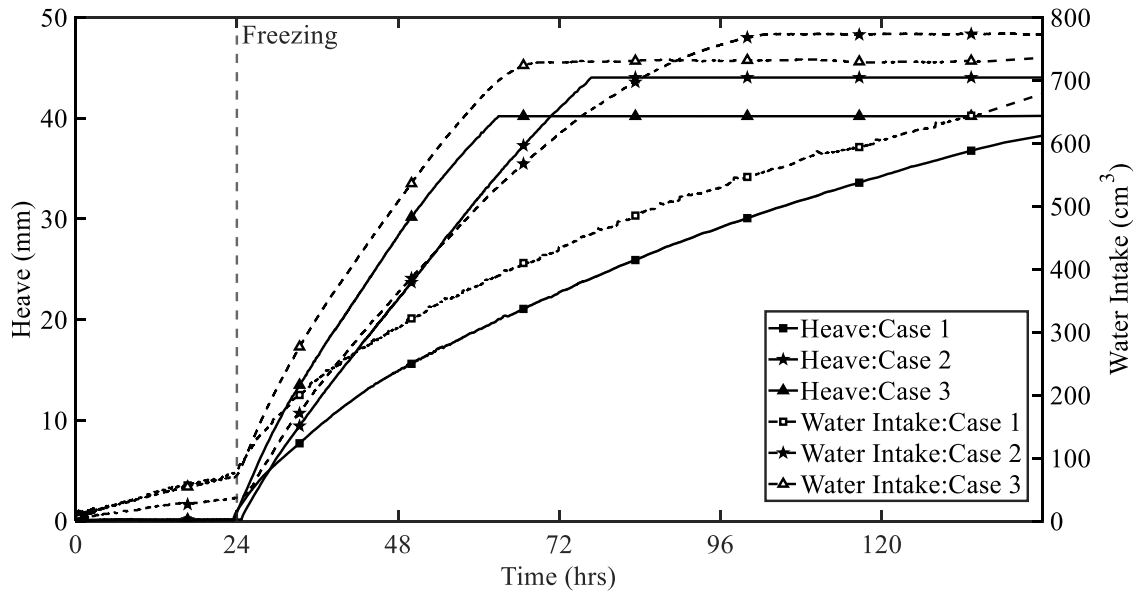


Figure 4. 7 Heave and water intake of the NC-BO specimens

For NC-BO (Figure 4.7), as anticipated, water intake ceased first in case 3. The higher freezing temperature in case 3 resulted in the faster formation of ice lenses at the bottom of the specimen compared to the other two cases. As the water inflow ceased, the frost heave stabilized earlier in case 3. In case 1, the freezing front did not propagate at the bottom of the specimen (Figure 4.4), so the water migration and heaving continued until the completion time of the test. During the test period, maximum heaving (44.04 mm) was observed in case 2. Heaving ceased at 76 hours in case 2. If the experiment continued longer, maximum heaving would have been observed in case 1 (estimated to be 44.92 mm after 192 hours), like IA-PC, as the entire specimen was not frozen, and water was continuously moving into the specimen. In case 1, after 120 hours of freezing, approximately 6.35 cm of the 15.2 cm specimen was frozen. Water migration and heaving would have been continued until the specimen was completely frozen.

The amount of heave during the experiment for both specimens is shown in Figure 4.8. NC-BO specimens had much higher heave compared to IA-PC. In case 3, NC-BO had a total heave of 40.19 mm compared to the 5.35 mm heave of IA-PC. The saturated hydraulic conductivity (Table 4.1) of NC-BO was 100 times higher than that of IA-PC, resulting in a larger volume of water intake, thus, more heaving. The heave rates for both specimens are presented in Figure 4.9. For both soils, the heave rate increased with the increase in temperature gradient. Larger

temperature gradients extract more heat, create more ice and generate more cryogenic suction per unit time. Case 3, with the maximum temperature gradient, exhibited the highest heave rates for both IA-PC (6.73 mm/day) and NC-BO (23.71 mm/day).

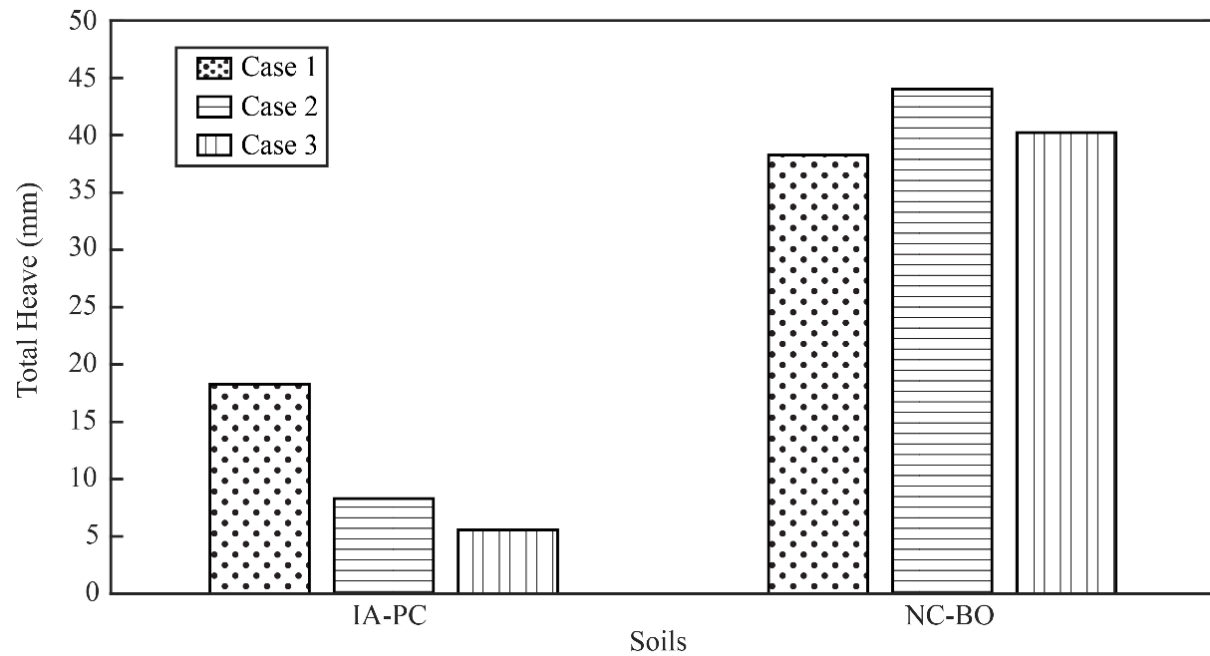


Figure 4. 8 Total heave of both the soil specimens

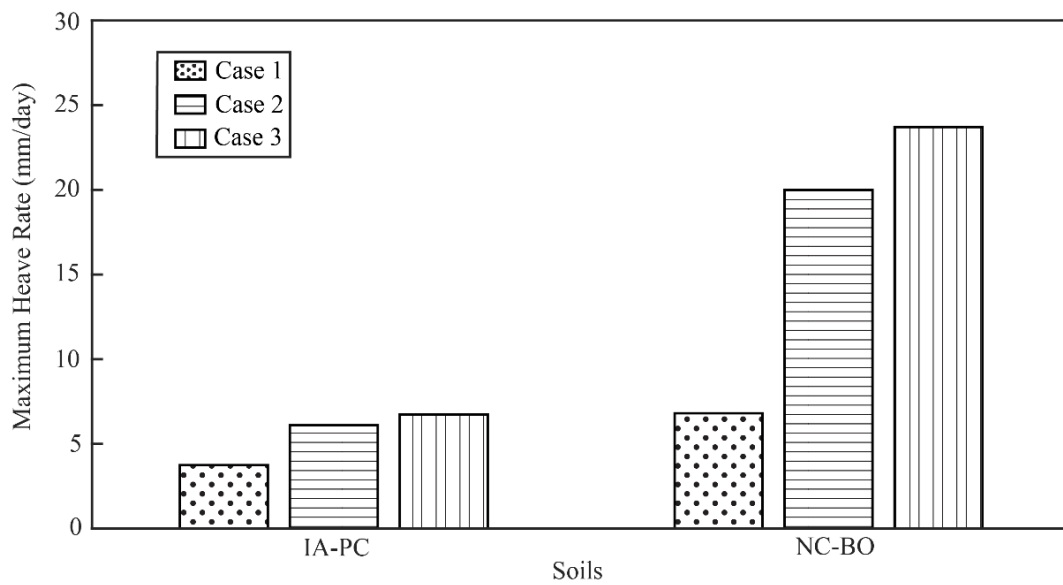


Figure 4. 9 Heave rate of both the soil specimens

In this study, the total heave and heave rate of soil specimens are primarily influenced by the soil's temperature gradient. These results provide a basis for gradient selection and testing duration. While the two soils are significantly different (e.g., silt vs. clay, a two-order of magnitude difference in hydraulic conductivity), a similar pattern is observed in terms of greater ultimate heave at lower temperature gradients. It can be anticipated from the test results that for any soil type, larger temperature gradients will result in higher rates of heaving. In contrast, smaller temperature gradients will result in larger total heaving if the freezing phenomenon persists for an extended period while there is access to water. If heat is removed too quickly, ice lense formation is limited and ultimate heaving is reduced. As such, laboratory-based testing with large temperature gradients may yield an underestimate of actual heave in the field. During subfreezing temperatures, the temperature gradient in the field typically ranges from 0.15-0.35 °C/cm (Genc et al., 2022). While lower temperature gradients are more field-relevant they require longer laboratory testing time (e.g., weeks to a month as compared to a <2 days) for the 0°C isotherm to penetrate a typical (e.g. as tested) soil sample. The ultimate magnitude of heave can be estimated (by extrapolating from the trend of the heave curve) without waiting for full penetration of the 0°C isotherm into a sample. Instead, it may be based on the extent of heave from a partial penetration of the 0°C isotherm such that penetration is more than the thickness of frozen fringe as ice lens form above the fringe. In particular, we propose that laboratory-based efforts to estimate field heave use lower temperature gradients (0.15-0.35 °C/cm) while ensuring that the 0°C isotherm has penetrated at least 1/2 of the specimen for a standard ASTM specified specimen of 15.2 cm height. The thickness of the frozen fringe is considered asymptotically small ~1 cm (Fowler, 1989b; Peppin & Style, 2013b).

Moisture Profile

Each specimen was split into six 2.54 cm-thick soil layers after thawing at the end of the frost heave experiment to evaluate soil moisture distribution throughout the soil depth. A moisture content sample was taken from the center of each layer. The moisture profiles of both soils are shown in Figure 4.10. The moisture content of IA-PC was higher at the bottom of the specimens for case 1 as it took a longer duration (35 hours for freezing, 11.4 to 14 cm) to freeze, and water was continuously entering during this period through this unfrozen soil region. For NC-BO, the specimen was not frozen at 8.9 cm in case 1 (Figure 4.4), so the water content was higher in that

region because of the frozen fringe. The moisture profile was nearly uniform for case 2 for both soils, as the entire specimen was frozen rapidly due to higher freezing temperatures. Figure 4.11 shows the pictures of both soil specimens before and after the frost heave test following thawing for case 1. It was visually observed that the NC-BO specimen seemed wetter and retained heave considerably even after the thawing process was completed.

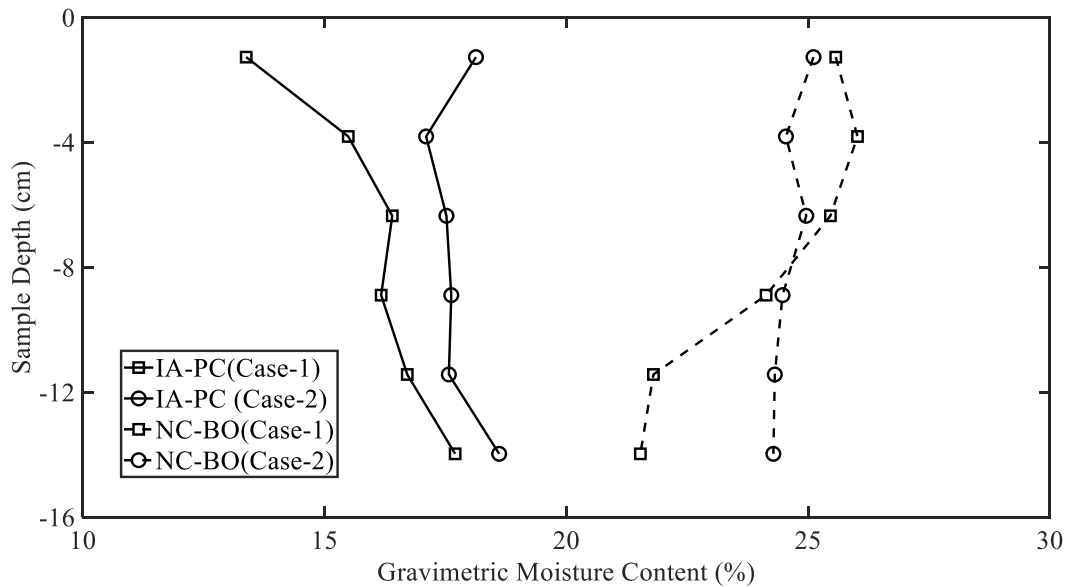


Figure 4. 10 Moisture profile of the soil specimens after frost heave test

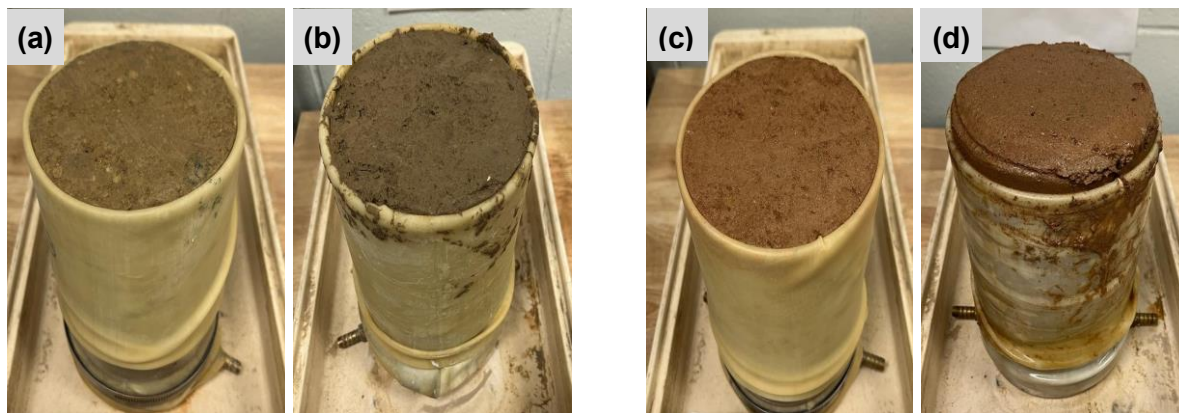


Figure 4. 11 Soil specimens before and after frost heave test a) IA-PC (before) b) IA-PC (after) c) NC-BO (before) d) NC-BO (after)

4.6 Conclusions

The temperature gradient plays a significant role during the frost heave phenomenon in soils by driving the water flux toward decreasing temperature. Therefore, this study was conducted to evaluate the effect of different temperature gradients and freezing temperatures on the frost heave potential of two different soils. The essential conclusions of this study are summarized below.

- The penetration of the freezing front is dependent on the thermal diffusivity of the soil. Due to higher thermal diffusivity of IA-PC soil, frost penetrated the IA-PC specimens faster than it did with NC-BO soil. A higher frost penetration rate was observed at higher temperature gradients as the heat was released rapidly due to lower freezing temperatures at the top of the specimens.
- Heaving is controlled by the extent to which water is available (open vs. closed system) and its ability (hydraulic conductivity) to move through the soil. Heaving ceased when water no longer entered the soil. The water intake, in turn, depends on frost penetration. As soon as the ice lens formed at the bottom of the specimens, water migration stopped due to a significant drop in hydraulic conductivity attributed to the presence of contiguous ice blocking subsequent water flow.
- Results of this study show that when the freezing temperature is sustained for a longer period, total heave and water intake are maximum for lower temperature gradients. Ice lenses are formed at shorter depths, and water keeps migrating from the unfrozen zone to the frozen fringe.
- The heave rate of soils increased with an increase in temperature gradient. Larger temperature gradients extract more heat, create more ice, and generate more cryogenic suction per unit time.
- Due to its high hydraulic conductivity, silty sand/silty clay (NC-BO) soil exhibited higher frost heave and water intake volume than that of low plasticity clay (IA-PC). The NC-BO specimen with the minimum temperature gradient had a higher moisture content close to the freezing front.

Temperature gradient and frost penetration rate can be considered as two major factors contributing to the frost penetration depth. The frost penetration depth is very significant in deciding the location of the treatment layer. The majority of the state agencies' frost mitigation guidelines suggest removing frost-susceptible materials to more than 50 percent of the frost penetration depth. The findings of this study will help in designing frost mitigation strategies for cold climates.

4.7 Acknowledgment

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CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study is to investigate the effect of soil properties and climatic conditions on frost action in soils. As part of the research endeavor, the effect of gradation on the frost susceptibility of four different soils from Iowa was investigated. Frost heave behavior of sandy and clay soils under multiple freeze-thaw cycles in both open and closed systems was also assessed. Furthermore, the effect of different temperature gradients and freezing temperatures on the frost heave potential of two different soils were evaluated. The more generalized conclusions and recommendations are provided in this chapter as follows:

5.1 Influence of Gradation on the Frost Susceptibility of Soils

- The amount of silt in soils significantly affected the frost susceptibility of soils. IA-PC soil had the highest maximum frost heave (30.9 mm) and heave rate (26.3 mm/day) due to its high silt content, followed by IA-BV.
- IA-CC was the least frost susceptible among the four soils, possibly due to its low silt content providing low hydraulic conductivity and capillarity for this soil.

5.2 Frost Heave Evaluation of Sandy and Clay Soils Under Open and Closed Systems with Multiple Freeze-Thaw Cycles

- Sandy soil with water supply experienced the highest heave during the first freeze-thaw cycle due to its high permeability. In clayey soil, the highest heave occurred during the second freeze-thaw cycle due to the formation of voids and micro-fissures after the first cycle.
- Both specimens showed a continuous increase in heave up to the 6th freeze-thaw cycle, after which the heave stabilized.
- The IA-PC specimen in the open system had a total heave that was 7 times greater than that in the closed system.
- Multiple freeze-thaw cycles are necessary to estimate soil heave potential accurately.
- Moisture levels in the specimens increased from bottom to top due to water movement towards the frozen fringe.

- This study contributes to the understanding of frost heave behavior in various soil types. In addition, it helps assess the extent of frost damage to pavements in different soil types under varying climatic conditions and moisture availability.

5.3 The Role of Temperature Gradient and Soil Thermal Properties on Frost Heave

- The frost penetration rate of soil depends on its thermal diffusivity. IA-PC soil has higher thermal diffusivity than NC-BO soil, so frost penetrates IA-PC specimens faster, especially at higher temperature gradients where heat is released more quickly.
- Soil heaving is mainly caused by water moving through the soil, which depends on its availability and hydraulic conductivity. Heaving stops when water no longer enters the soil. Once an ice lens forms at the bottom of the specimens, water migration stops due to the ice blocking water flow.
- Sustained freezing temperatures lead to maximum heaving and water intake at lower temperature gradients. As a result, ice lenses form at shallower depths, and water moves from the unfrozen zone to the frozen fringe.
- Soil heaving increases as temperature gradients increase. Higher temperature gradients extract more heat, create more ice, and generate more cryogenic suction per unit of time.

5.4 Recommendations

Several recommendations for future studies on frost action are provided as follows:

- To investigate frost penetration depth in different soils under varying climatic conditions, it is recommended to use thermal modeling that accounts for soil thermal properties and temperature gradient in the field
- Performing Mercury Intrusion Porosimetry tests can help to comprehend how pore size changes with freeze-thaw cycles, contributing to a better understanding of soil behavior.
- To visualize ice lens formation and location and frozen fringe thickness for different soil types, conducting frost heave tests with a camera in a large box setup is recommended.