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

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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 flow of water 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°C/cm, 0.52°C/cm, and 0.78 °C/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°C/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 higher temperature gradient of 0.78 °C/cm and soil with higher thermal diffusivity of 0.684 mm^2/s. The results of this study can be used to validate numerical models and develop engineered solutions that prevent frost damage.

Keywords: Frost susceptibility, frost heave, frost penetration, temperature gradient, ice lens

INTRODUCTION

In cold regions, repeated cycles of freezing and thawing (i.e., frost action) cause damage to transportation infrastructure, including pavements and granular roadways (1–3). 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(4). Some water typically remains unfrozen in soils below the freezing point of water due to the capillarity and surface energy of soil particles(5). The unfrozen water content influences the soil's thermal and mechanical properties, which dictate the soil's water migration and frost heave(6). Water migration and frost heave processes have been studied under different scenarios in the past(7–10). Naqvi et al. (8) 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. (7) 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 (9) 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. (10) 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. (11) 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 ˚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(6,12,13).

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(10,11). 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(14) 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.

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 (15). 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 D 6913 (16) and presented in **Figure 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 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 (17) frost susceptibility classification, which implies that both soils are frost-susceptible (medium to high).

Figure 1 Grain size distribution of the soils

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(14). 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 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°C/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°C/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°C and a temperature stability of ±0.005°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 (14) 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 µm. 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°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 cm 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 (14) is depicted in **Figure 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 1 Physical properties of the soils

Soil Properties	**IA-PC**	**NC-BO**
Specific Gravity, G_s (ASTM D854-14)(18)	2.80	2.67
Liquid Limit, LL (%) (ASTM D4318-17)(19)	37	38
Plasticity Index, PI (%) (ASTM D4318-17)(19)	13	NP
Silt content (%) (75 µm–2 µm)	86.2	34.0
Clay content (%) (< 2 µm)	12.0	4.6
Optimum Moisture Content (%) (ASTM D698-12)(20)	17.3	15.6
Max. Dry Unit Weight (kN/m^3) (ASTM D698-12)(20)	16.7	16.9
Saturated Hydraulic Conductivity (cm/s)	5.02×10^{-8}	6.34×10^{-6}
USCS Classification (ASTM D2847) (21)	CL	SM/SC
AASHTO Classification(22)	A-6	A-4
Frost Susceptibility Group$^+$ (17)	F3	F3

*N.P.- Non-Plastic
$^+$F1-Low frost susceptibility; F4-Very high frost susceptibility

Table 2 Testing conditions of the soil specimens

Soil type	**Case**	**Initial conditioning Temperature (˚C)**	**Temperature Boundary(˚C)**		**Temperature Gradient (˚C/cm)**	**Freezing Duration (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 2 Frost heave testing setup (23)

RESULTS AND DISCUSSION

Temperature Distribution

The temperature distributions of IA-PC and NC-BO soil specimens for three different cases (**Table 2**) at various depths are shown in **Figure 3** and **Figure 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 3)**, the freezing front moved much more slowly for NC-BO specimens **(Figure 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 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 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 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 3 Time needed for frost penetration for 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.** 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/ m^3K) is higher than that of IA-PC specimens (2.29 MJ/m^3K), 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(24). Thermal diffusivity can be expressed by **Equation 1**(25,26).

$$\alpha = \frac{k}{\rho Cp} \qquad (1)$$

where α is the thermal diffusivity, k is the thermal conductivity, ρ is density, and Cp 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 mm^2/s) is higher than that of the NC-BO specimen (0.59 mm^2/s), so the frost front penetrated the IA-PC specimen more quickly. **Figure 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(26). 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 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 5 Frost penetration rate of soil specimens during freezing process

Heave trends and water intake

Figure 6 and **Figure 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 (27,28). 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 6 Heave and water intake of the IA-PC specimens

For IA-PC (**Figure 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(29). 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 7 Heave and water intake of the NC-BO specimens

For NC-BO (**Figure 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**), 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 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 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 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 8 Total heave of both the soil specimens

Figure 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 (30). 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 as asymptotically small ~1 cm (31,32).

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 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**), 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 11** shows the pictures 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 is completed.

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

Figure 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)

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.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: M. Sadiq, M. Naqvi, B. Cetin, J. Daniels ; data collection: M. Sadiq, M.Naqvi; analysis and interpretation of results: M. Sadiq , M. Naqvi, B. Cetin ; draft manuscript preparation: M. Sadiq , M. Naqvi, B. Cetin, J. Daniels. All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF CONFLICTING INTERESTS

The authors do not have any conflicts of interest to declare.

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