Investigating the Frost Action in Soils

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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 the availability of water, pore fluid composition, rate of heat loss, and soil type. Similarly, 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, grainsize distribution, and pore fluid. As part of a larger nationwide project, the current study evaluates the frost heave potential of soils collected from Alaska, Iowa, and North Carolina. 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. The results of the study showed that amount of silt and clay content in the soil have a direct effect on the frost heave phenomenon. Soils that have higher silt content and less clay content had higher heaving. It was determined that all the soils were highly frost susceptible and had high-heave rates up to 28.4 mm/day. The maximum frost penetration depth and frost penetration rate were 114 mm and 260 mm/day, respectively.

Keywords: Frost susceptibility, frost heave, frost penetration, segregation, ice lens formation

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 phase of water which results in the formation of ice lenses in a soil matrix while thaw weakening results from 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 mostly 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 lens 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 the 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 contents and higher hydraulic conductivity. The frost susceptible soil classification of the U.S. Army Corps of Engineers based on the grain size distribution is 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 formation of ice lenses are dependent on environmental factors such as pore fluid composition, temperature gradient, location of the water table, vertical effective stress, and rate of cooling (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 is decreased. Thus, a rise in cooling rate during a fixed freezing time usually results in higher frost penetration depth and greater frost heave (Sheng et al. 2013).

In this study, one-dimensional freezing tests were carried out for soil samples collected from different climatic regions including Alaska, Iowa, and North Carolina. 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 eight thermocouples placed inside the specimens. The temperature profile of soil and heaving trends were monitored during freezing and thawing periods. The water intake during the testing was also observed for the Alaskan soil. The parameters were used to evaluate total heave, heave ratio, frost penetration depth, and frost penetration rate during testing. The temperature profile of the soil and the water inflow rate were correlated with the heaving trend during the freezing period.

MATERIALS AND METHODS

The soils were collected from Fairbanks in Alaska (AK-FB), Clinton County in Iowa (IA-CC), and Asheville in North Carolina (NC-AS). These soils exist in different climatic regions and are subjected to different magnitudes of the freezing index. 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 1. The grain size distributions of soil are presented in Figure 1. The ratio of silt to clay was determined to be 3.4, 2.33, 7.2 for AK-FB, IA-CC, and NC-AS, respectively.

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 6 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.

Table 1. Summary of soil index properties and classification

	AK-FB	IA-CC	NC-AS
Specific Gravity, G_s (ASTM D854-14)	2.65	2.63	2.63
Liquid Limit, LL (%) (ASTM D4318-17)	41	51.62	38
Plasticity Index, PI (%)(ASTM D4318-17)	NP*	28.01	NP*
Silt content (%) (75 µm–2 µm)	63.1	50.7	34
Clay content (%) (< 2 µm)	18.6	21.7	4.7
Optimum Moisture Content (%) (ASTM D698-12)	20.9	20.2	19.2
Max. Dry Unit Weight (kN/m^3) (ASTM D698-12)	14.8	15.9	15.6
Hydraulic Conductivity (cm/s)$^{\#}$	3.86e-05	3.75e-05	1.78e-03
USCS Classification	ML	CH	SM/SC
AASHTO Classification	A-5	A-7-6	A-4
Frost Susceptibility Group^{+}	F4	F3	F3/F4

*NP- Non-Plastic
#Calculated using Wang, et al. (2017)
$^{+}$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

Each specimen was set on a heat exchange plate that was connected to a circulating bath. Another heat exchange plate, also connected to a circulating bath, was placed at the top of the specimens for replicating ground freezing conditions from the top. 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 -30º C to 200º 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 º 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. 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 -3º C to -12º C of circulating fluid took 30 minutes during testing. A surcharge weight of

2.25 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 source of water 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. 8 T-type thermocouples were inserted inside of each soil specimen that were 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 4º C temperature. The freezer was filled with packing peanuts to cover the soils specimens completely for having a controlled environment and minimizing any lateral heat loss so only 1D freezing occurs.

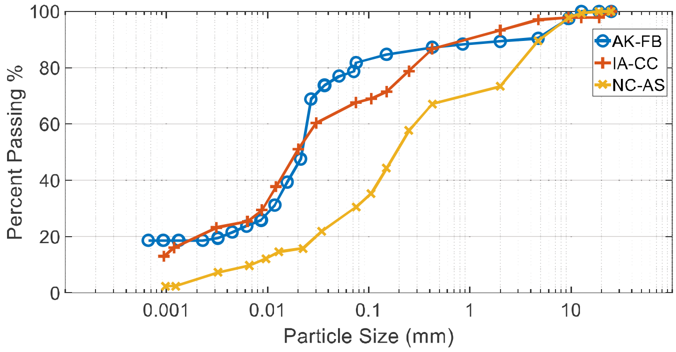

Figure 1. Grain size distribution of soils (ASTM D6913).

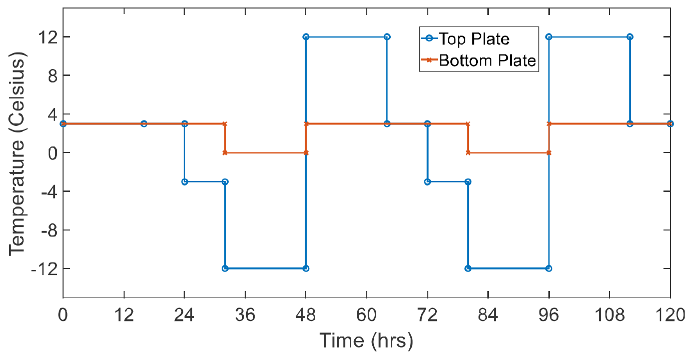

Figure 2. Temperature program in circulating bath for top and bottom heat exchange plates.

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 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 testing was conducted for 5 days to apply two freeze-thaw cycles on each specimen.

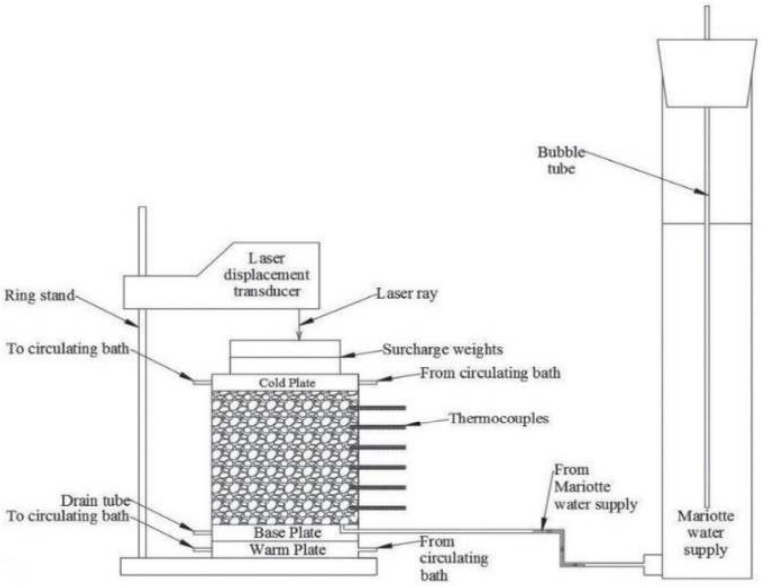

Figure 3. Frost heave testing assembly (Adopted from Mahedi, et al. 2020).

RESULTS AND DISCUSSION

The frost heave test setup provides temperature and displacement data for two freeze-thaw cycles. Using this information, parameters such as heave rate, the total amount of heave, frost penetration depth, and frost penetration rate were calculated. Water intake during different stages of testing was measured as well. One thermocouple was placed inside the freezer for monitoring the ambient temperature. The temperature of the freezer stayed between 3º C and 5º C during testing.

Total Heaving, Heave Rate, Heave Ratio

Figure 4 shows the trend of frost heave-thaw settlement plots of three soils. All soils experienced heaving during freezing cycles and consolidation during thawing cycles as expected. The first 24 hours of testing provide a conditioning period with both bottom and top heat exchange plates at above freezing temperature. After this conditioning period, the first freezing cycle (24 hours) and thawing cycle (24 hours) began. No heaving was observed in AK-FB and IA-CC 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. In addition, ice nucleation sometimes requires a physical disturbance, e.g., through specimen vibration (Daniels et al. 2003). Only NC-AS soil showed heaving during the first 8 hours of the freezing period. It is believed that the high thermal conductivity of the soil due to the large percentage of the sand fraction may have induced heaving even with this low-temperature gradient. However, after the first 8 hours of the freezing period, substantial heaving starts in all soils. It is because the top heat exchange plates temperature was changed from -3º C to -12º C which is significantly below the freezing temperature causing substantial ice lens formation and subsequent heaving. All the soils followed similar heaving and thawing trend during the test. AK-FB and NC-AS showed significant heaving in the first cycle only. On the other hand, IA-CC heaved less during the first freezing cycle. These results suggest that high silt content and low clay content of the soils cause higher total heaving. A similar trend was observed in the second cycle with NC-AS having the highest heaving followed by AK-FB and IA-CC. IA-CC showed a significant increase in the heaving in the second freezing cycle compared to the first cycle. The increase in the heave of IA-CC 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). The IA-CC soil has high clay content suggesting low hydraulic conductivity at the start of the test. 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.

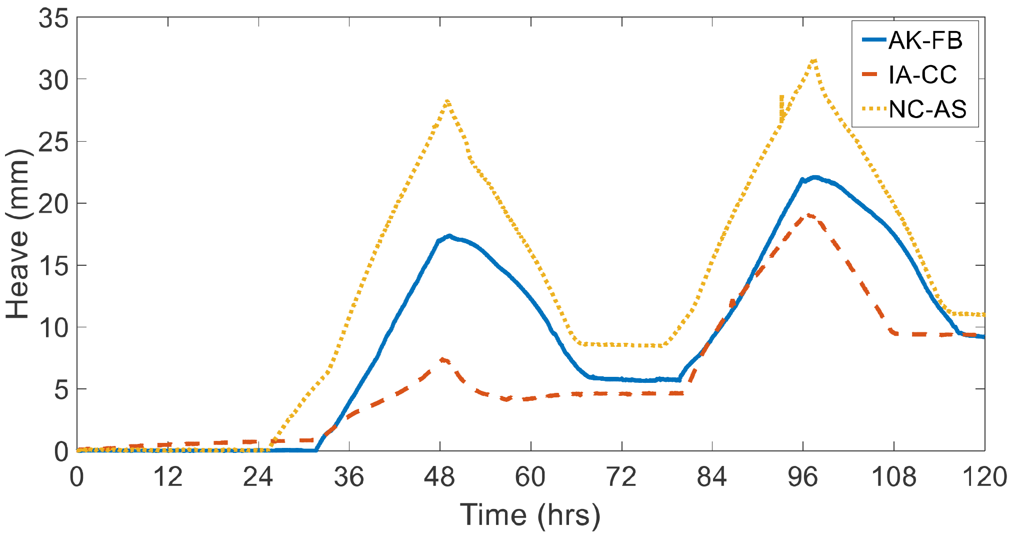

Figure 4. Heave and thaw of different soils during frost heave testing.

The maximum heave amounts and heave rates of different soils during the first and second freezing periods are presented in Figures 5 and 6. Figure 5 shows a quantitative comparison of the ultimate heaving of each soil type at each freezing cycle. The results indicate that each soil has a different maximum heaving amount. The maximum heave was observed for NC-AS soils with 28.3 mm heave in the first cycle while the minimum heave was observed for IA-CC soil (having amount is 7.38 mm) in the first freezing cycle. The high heaving in NC-AS soil may be attributed to high silt and low clay contents. The silt particles and its high porosity provide affinity for high moisture content and may yield more water for greater ice formation and result in higher heaving (Pollard 2017). However, the low hydraulic conductivity of IA-CC due to high clay content could be the explanation for lower heaving in the soil. Because of the high clay content, the soil has a low permeability reducing the extent to which water flows into the frozen fringe. This inhibits the growth of ice lens (Sheng, et al. 2013). Figure 6 shows the heave rate of soils which is obtained by drawing a tangent line to the heaving curve as described in Zhang et al. (2016). Similar to the total heave trend, the maximum heave rate was also observed for NC-AS soil whereas the minimum heave rate was observed for IA-CC. The heave rates observed for AK-FB, IA-CC, and NC-AS were 17.2 mm/day, 5.9 mm/day, 28.4 mm/day, respectively for the first freezing cycle; and 15.6 mm/day, 14.9 mm/day, and 23.1 mm/day, respectively for the second freezing cycle. According to the US Army Corps of Engineers Frost susceptibility classification, which is based on heave rate, all the soils tested to 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 AK-FB, IA-CC, and NC-AS were determined to be 6.3%, 6.4%, 7.5%, respectively.

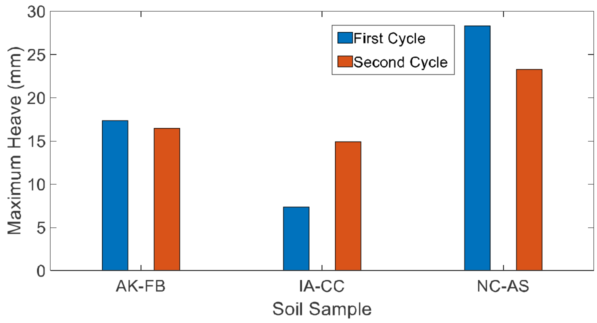

Figure 5. Maximum heaves of soils during two freezing cycles.

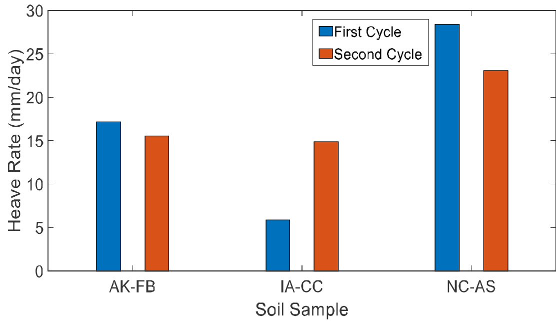

Figure 6. Heave rates of soils during two freezing cycles.

Frost Penetration Depth and Rate

Figure 7 shows the spatial and temporal distribution of soil temperature of soils tested in this study during frost heave testing. 8 thermocouples numbered from 1 to 8, where number 1 was located at the bottom of the specimens while number 8 was placed at the top of the specimens (Figure 3). Results showed that the maximum frost penetration depths were 8.8 cm, 11.4 cm, and 8.8 cm for AK-FB, IA-CC, and NC-AS, respectively (Figure 7) during the two cycles.

The temperature of the soils increases from top to bottom as shown in Figure 7. Higher variations in temperature are observed in the top portion of the specimen whereas these variations decrease towards the bottom of the soil specimens. Sharp trends in temperatures profile are observed at the start of freezing and thawing periods as well.

Frost penetration rate is defined as the rate at which freezing isotherm moves into the specimen, which for these experiments is presumed to be 0º C (Chamberlain 1981). The ice lens formation was assumed to start at 0 º C and the freezing point depression was neglected for the calculation. Figure 8 shows the frost penetration rate of three soils. IA-CC showed the highest frost penetration followed by AK-FB and NC-AS with 260.4 mm/day, 103.9 mm/day, 85.2 mm/day respectively. The frost penetration rate and depth depend on the thermal properties and moisture content of the soil. The amount of water present in the soil dominates the frost penetration as a high amount of heat units (Btu) is required to freeze each gm of water compared to soil grains. All the soils have similar moisture contents during sample preparation as shown in Table 1. It was observed that AK-FB and NC-AS had significant water intake during saturation and swell notably which may have increased the void ratio of the soil. On the other hand, water intake by IA-CC soil during saturation was minimal and no swelling was observed. Therefore, due to the low degree of saturation of IA-CC soil, which caused less amount of heat required to freeze the soil, the frost penetration of IA-CC soil was higher than that of AK-FB and NC-AS soil.

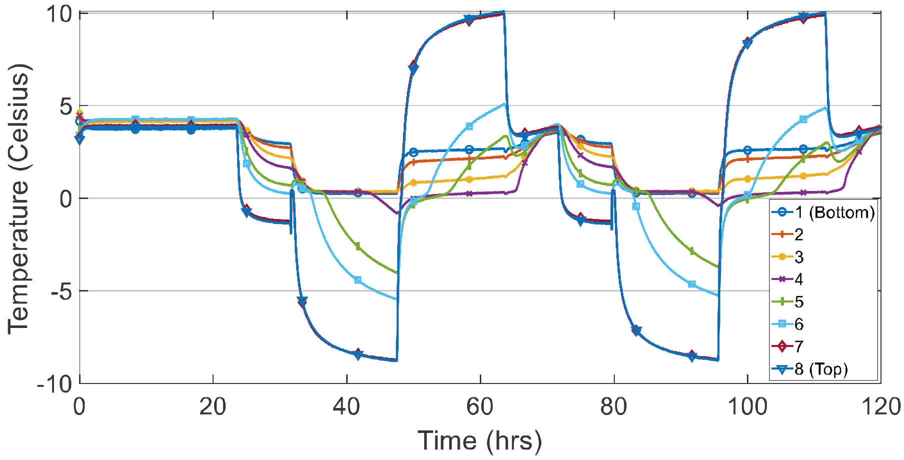

Figure 7a. Temperature Profile with Depth of AK-FB Soil.

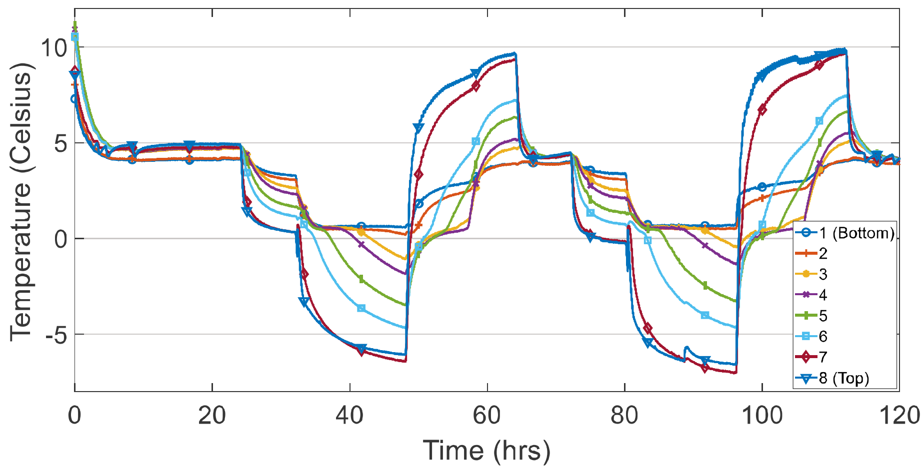

Figure 7b. Temperature Profile with Depth of IA-CC Soil.

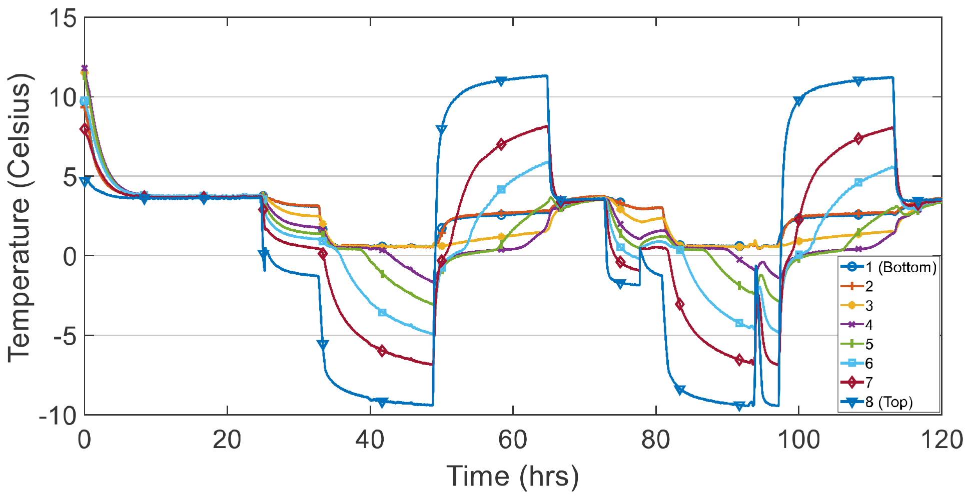

Figure 7c. Temperature Profile with Depth of NC-AS Soil.

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. All the soils showed similar trends of water intake during testing. As expected, the water intake by the soil is high during the freezing process (Figure 9). This occurs as the ice lens formation begins during the freezing cycle and the ice segregation starts taking place due to water migration from the unfrozen zone to the frozen fringe zone.

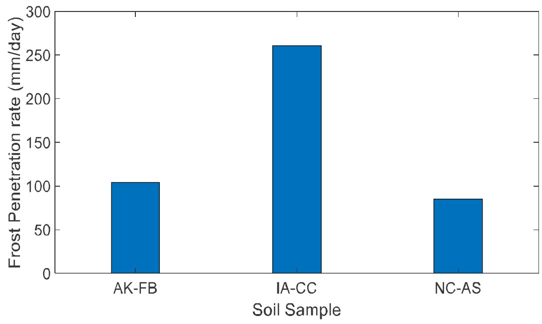

Figure 8. Frost Penetration rate (mm/day) for different Soil.

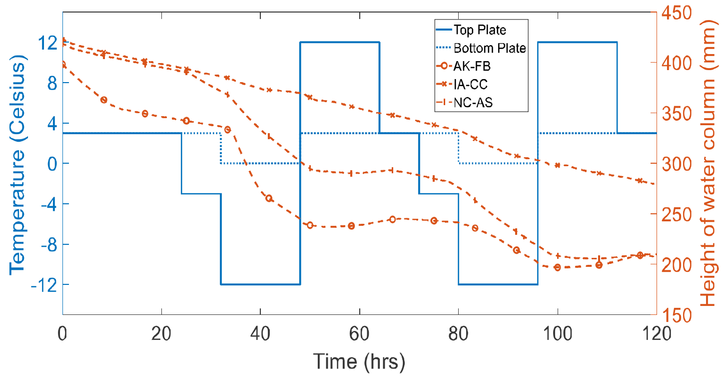

Figure 9. Water intake by soils during testing.

CONCLUSIONS

Frost heave testing of soils from Alaska, Iowa, and North Carolina was conducted for determining their frost susceptibility. The results showed that the amount of silt and clays in soils had significant effects on the frost susceptibility of soils. The soils with high silt content and low clay content showed a higher amount of frost heaving. The maximum frost heave (28.3 mm) and heave rate (28.4 mm/day) were observed for NC-AS soil due to its high silt and low clay contents followed by AK-FB. The IA-CC was less frost susceptible than the other two soils possibly due to its high clay content providing very low hydraulic conductivity for this soil. The low hydraulic conductivity limits the water migration to the frozen fringe zone thus causing low heaving. The maximum frost penetration rate of 260.4 mm/day was found in IA-CC. The water intake was determined to be maximum during the freezing cycle because of water migration towards frozen fringe due to ice lens formation.

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