Frost Susceptibility Evaluation of Clay and Sandy Soils

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ABSTRACT

Frost action in soils cause 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 7 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 were used in estimating the frost heave potential of soils in different environmental conditions.

Keywords: Frost susceptibility, frost heave, heave rate, heave ratio, water presence

INTRODUCTION

The frost action in soils affects the design, construction, and maintenance of geostructural systems such as pavement challenging. The formation of ice lenses in soils can cause significant heaving followed by a substantial strength reduction during thawing which may lead to a systematic failure of the infrastructure. Current strategies for mitigating damages due to freeze-thaw (F-T) is estimated yearly cost of over $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 type of 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 is dependent upon the suction and permeability of the soil (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 prone to be most frost susceptible. 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., 2016; 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 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 different soil types, clay, and sandy 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.

MATERIALS AND METHODS

The selected two soils are a 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. In the field, IA-PC experiences a wet, hard-freeze, spring thaw while the NC-BO experience a wet, F-T cycling condition. Table 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 1. Both of the 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 1 shows that the fines contents of IA-PC soil is 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 1) and this indicates that both soils are frost susceptible (ranging from low to very high).

Table 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 μm–2 μm)	86.2	34.0
Clay content (%) (< 2 μm)	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)	5.02e-08	6.34e-06
USCS Classification	CL	SM/SC
AASHTO Classification	A-6	A-4
Frost Susceptibility Group$^+$	F3	F3

*NP- 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 using freezing-thawing test equipment as shown in Figure 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 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 6 acrylic rings of 2.54 cm in height to restrain the sample laterally. After compaction, the specimens were placed over a base plate that was connected to a Marriot cylinder to act as a water source for the open system. For specimens with a closed system, the base plate was not connected to the water supply. All the specimens were saturated for 24 hours.

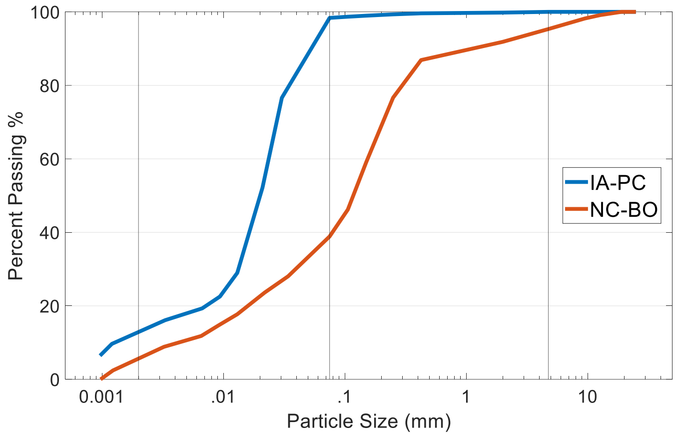


Figure 1. Grain size distribution of soils (ASTM D6913)

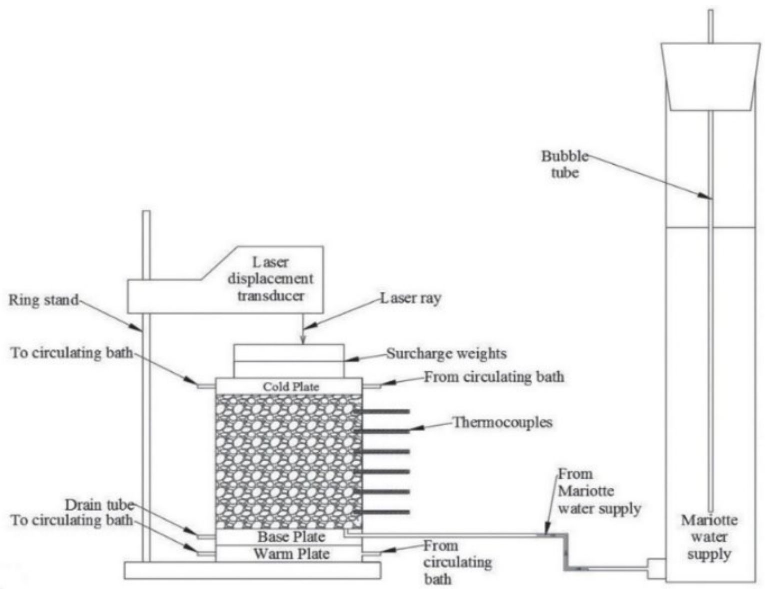


Figure 2. Frost heave testing assembly (Adopted from Mahedi, et al. 2020)

After saturation, the specimens were assembled for frost heave testing inside the chest freezer which was programmed to maintain a temperature of 4º C. The sample along with the base plate was placed on a bottom heat exchanger plate (also called a warm plate). Similarly, another heat exchanger plate (also called a cold plate) was placed at top of the specimen to simulate the top-down freezing conditions. These warm and cold plates were connected to a circulating bath for controlling the temperature at the bottom and the top of the specimen. The fully programmable circulating baths have a temperature range of -30º C to 200º C and can quickly change the temperature of the circulating fluid. The temperature program of the two circulating baths is provided in Figure 3. Since the specimens were subjected to freezing temperatures, the circulating fluid was prepared by mixing water and ethylene glycol at a ratio of 1:1. A surcharge weight of 2.25 kg was placed on each specimen. The specimens subjected to an open system were connected to a Marriot bottle through a base plate and a constant head of 2.5 cm was applied using a capillary tube during the experiment.

The heaving of the specimen during the experiment was measured using lasers which had a measuring range of 5 cm. A pressure transducer at the base of the Marriot bottle was installed to measure the amount of water going inside the specimens during frost heave testing. The diameter of the Marriot bottle was 7.62 cm. Thus, every unit cm water intake means 7.07 cm^3 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 except the F-T cycles were extended from two to ten. After the experiment, the specimens were disassembled and sliced into 6 pieces to determine the gravimetric moisture content of the specimens from top to bottom.

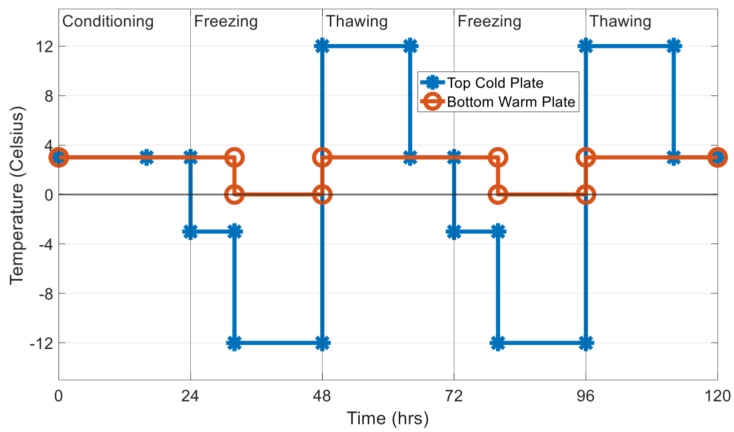


Figure 3. Temperature program in circulating bath for top and bottom heat exchange plates

RESULTS AND DISCUSSION

Total Heaving, Heave Rate, Heave Ratio

Figure 4 presents the frost heave and thaw settlements under a number of 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 cycles and settlement during thawing cycles as expected. For an open system, it is clearly 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 due to the water available in the soil for the closed system being limited thus its conversion to ice lenses during freezing temperatures is at minimal levels. 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).

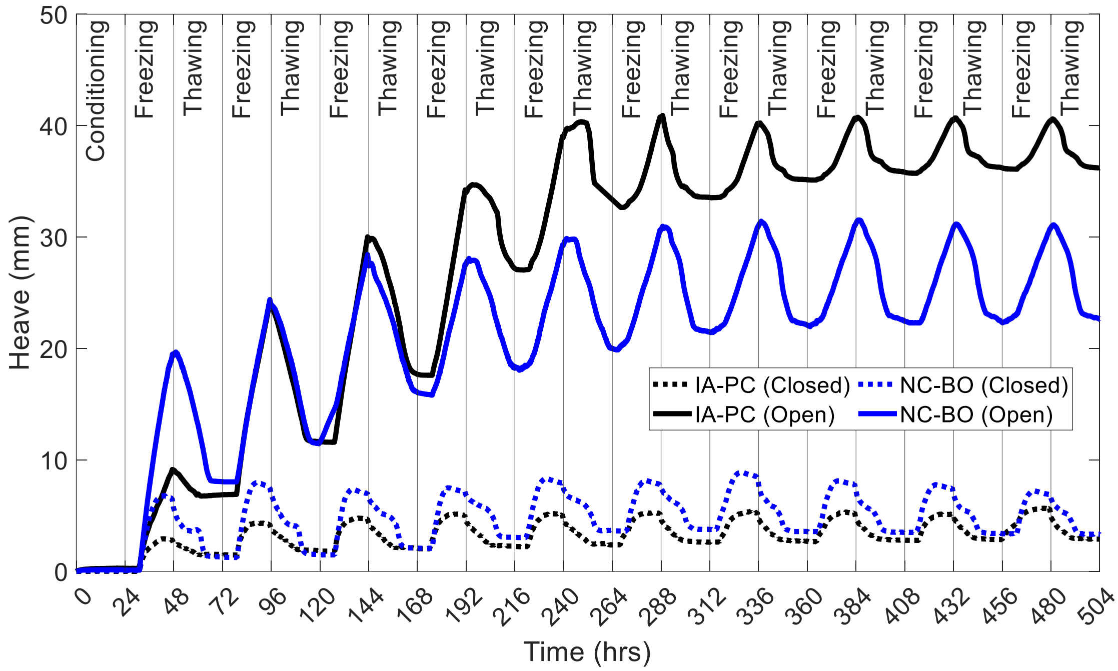


Figure 4. Heave and thaw of different soils during frost heave testing

For soils with the open system, the heave was considerably higher compared to the closed system. This is largely in part due to the water migration induced by the temperature gradient (Xu et al. 1999). A temperature gradient in the freezing 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 yields to large ice formations leading to a greater magnitude of heaving (40.91 for IA-PC). This is also evident from the amount of 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 finally 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 1) as a result of high clay contents in IA-PC. After the first F-T cycle, the formation of large voids as well micro fissuring may have lead 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). 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 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 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 that of 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 gauge the frost heave potential of soil and more F-T cycles may provide better insight into soil behavior during F-T conditions.

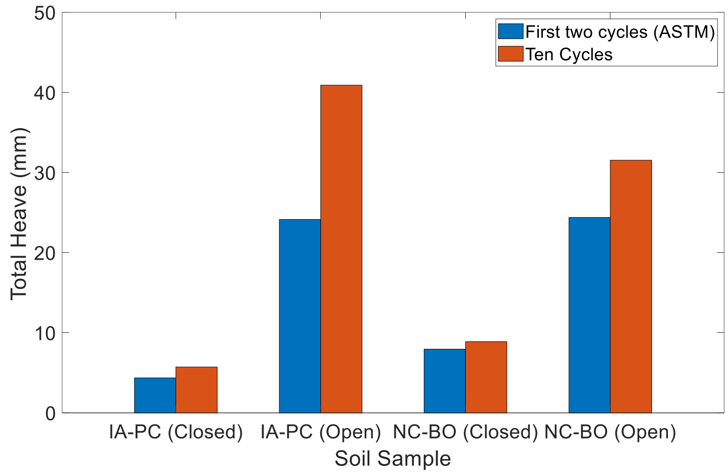
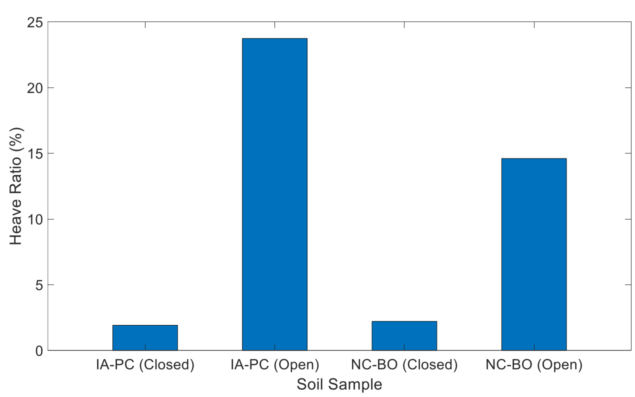


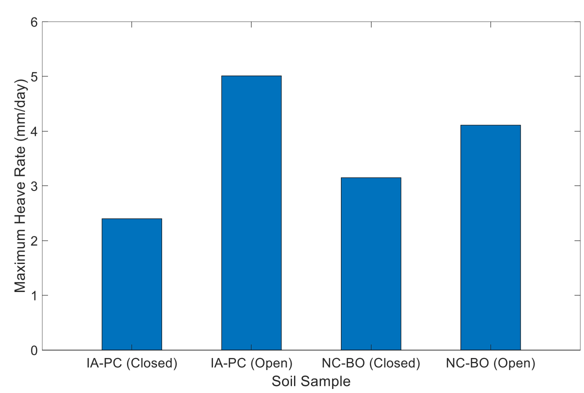
Figure 5: Maximum Heave after two and ten F-T cycles

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 10^{th} F-T cycle is considered to calculate the frost heave increment. The frost heave ratio of the specimens is shown in Figure 6a. 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.

$$\xi = \frac{\Delta h}{H_f} * 100\% \quad (1)$$



(a) Frost Heave ratio



(b) Maximum Heave rate

Figure 6: Frost Heave parameters

ASTM D5918 suggests the calculation of the heave rate from the first 8 hours of the freezing period of the first and the second freezing cycle. For the present study, the larger magnitude from the two cycles was considered as the heave rates of the soils. Figure 6b shows the heave rates of both soils. Soils with open system IA-PC (5.01 mm/day) and NC-BO (4.11 mm/day) had higher heave rates compared to closed system conditions for IA-PC (2.4 mm/day) and NC-BO (3.15 mm/day). Based on the heave rates of the tested soils, they can be classified as medium to highly frost-susceptible soils.

Water Intake

Figure 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 that of 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 were similar.

The moisture content of the specimens with depth after the F-T test is shown in Figure 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.

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 estimates 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 movement of water 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 various climatic conditions and moisture availability.

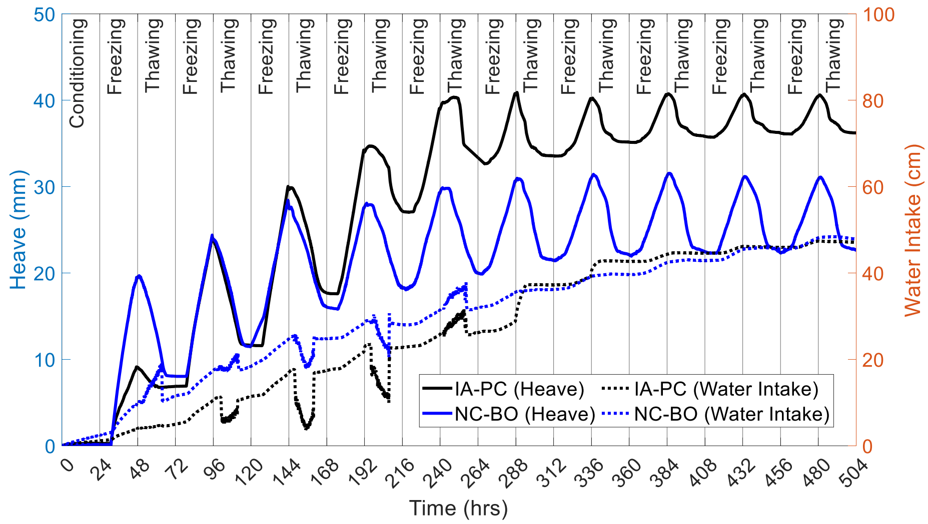


Figure 7. Water intake by soils during testing

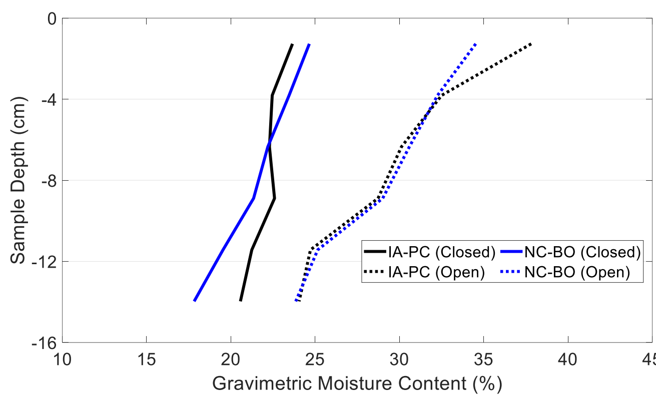


Figure 8. Gravimetric moisture contents of soils after frost heave testing

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