Effect of Salt Concentrations on the Freeze-Thaw Behavior of Soils

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ABSTRACT

The occurrence of freeze-thaw cycles within the soil can result in adverse consequences such as frost heaving and a reduction in stiffness during thawing. The freezing behavior and subsequent thaw-weakening of soils can be influenced by the salt concentration in soils, which is affected due to road deicing operations during the winter. The presence of salt concentrations in soils induces a phenomenon known as freezing point depression, resulting in a decrease in the formation of ice within the soil. Concurrently, an elevated concentration of salt triggers osmotic suction as a result of the expulsion of ions towards the freezing front during the process of ice formation. These two phenomena can potentially result in either a decrease or an increase in the vulnerability of soils to frost action. The present study aims to examine the influence of varying salt concentrations on the freeze-thaw susceptibility of soil. The soil samples were treated with various salt concentrations, including 0.2%, 1%, and 5% NaCl solutions, as well as a control prepared with deionized water. The experiment involved determining the freezing point depression resulting from the presence of salt, and it was observed that the degree of depression increased in proportion to the concentration of salt. The specimens underwent a freeze-thaw test in a one-dimensional manner. During the experiment, measurements were taken for heave, temperature, and water intake. Additionally, the moisture content of the specimen was determined at various depths following the freeze-thaw test. In order to comprehend the distribution of salt within the specimen following a freeze-thaw cycle, the salt concentration of the specimens was assessed at various depths. This was achieved by measuring the electrical conductivity of pore water using a 1:5 soil-to-water extraction method. The findings indicated that the freezing point depression exerted a greater influence compared to osmotic suction, resulting in a decrease in the formation of ice within soils. The specimens treated with salt exhibited a reduction in the heave of up to 31% when compared to the control prepared with deionized water, due to lower ice segregation. Large variations in moisture content and salt concentration were observed between different specimens and along the specimen height after the freeze-thaw test. It can be concluded that freezing point depression has a greater influence over osmotic suction at above salt concentrations during freeze-thaw. Hence, the presence of salt can aid in the mitigation of freeze-thaw damage in soils.

INTRODUCTION

The key environmental component that has a considerable impact on the performance of pavement is frost action. Based on available reports, it has been found that roughly 60 percent, of pavement failures occur during the spring season. The failures have been attributed to frost action (Doré & Zubeck, 2009; Kim & Newcomb, 1991). According to a study, it has been observed that the deterioration of pavement resulting from the cyclical freezing and thawing during different seasons contributes significantly, to up to 75% of the total damage (Dore et al., 2005). The United States spends more than 2 billion dollars annually on the maintenance and restoration of pavements as a result of frost action (DiMillio, 1999). Based on the findings of the U.S. Geological Survey in 2020, it was ascertained that a significant proportion, specifically 43%, of the overall salt utilization in the United States is designated for the purpose of deicing highways. The yearly usage of salt for road deicing in the United States amounts to approximately 20 million tons (Gross, 2022). Among the deicing salts that are frequently employed, sodium chloride (NaCl), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$) are the most prevalent, with sodium chloride being the most extensively utilized. The utilization of road deicing salts, specifically sodium chloride, has been observed to exert a prolonged influence on soil electrical conductivity (EC) and sodium concentrations, persisting beyond the winter period and continuing into the summer season. Subsequently, these ions are released into the surrounding environment, potentially leading to a range of environmental issues (Claros et al., 2021). Hence, comprehending the impacts of road deicing salt on frost heave prevention can facilitate the efficient utilization of road salt while minimizing environmental consequences.

The freezing point of soil is reduced due to the existence of solutes in the pore water of soil, and this depression is more noticeable when the water content is lower. Moreover, the freezing point of soil is predominantly affected by chloride (Cl^-) ions as opposed to carbonate $(CO_3)^{2-}$ and sulfate $(SO_4)^{2-}$ ions. Likewise, with regards to cations, the hierarchy of influence is as follows: potassium ions (K^+) exhibit the greatest impact, followed by sodium ions (Na^+), calcium ions (Ca^{2+}), and magnesium ions (Mg^{2+}) (Bing & Ma, 2011; Shah & Mir, 2022b). Moisture migration is primarily facilitated by the process of convection, whereas both convection and diffusion contribute to salt migration (Liu et al., 2021). The phenomenon of salt diffusion migration is likewise driven by a spatial gradient in concentration, leading to the movement of salt from the frozen area to the unfrozen area. The intricate issue of moisture and salt migration in soils during the process of freezing and thawing is a multifaceted phenomenon that involves the thermodynamics of the system comprising soil, ice, salt, water, and the matrix, as well as many phase transitions. The complex nature of this process possesses the capacity to cause substantial damage to both soils and structures, resulting in phenomena such as frost heave, thawing settlement, salt expansion, and collapse.

The accurate prediction of frost heave in saline soils has been a topic of interest, but it has faced challenges due to the complex interplay between osmotic and matric forces (Marion, 1995). An increase in osmotic potential is expected to result in an elevation in heaving, as it has a positive link with thermal conductivity and subsequently enhances frost penetration. Additionally, it results in an increased flow of water towards the frozen fringe. However, it is crucial to acknowledge that osmotic potential has a significant role in lowering the freezing point (freezing point depression), thereby decreasing the extent of ice formation. The reduction in frost heave is commonly ascribed to the presence of salts (Liu et al., 2021; Sarsembayeva & Collins, 2017; Shah & Mir, 2022a).

Nevertheless, certain investigations have indicated inconclusive and unpredictable outcomes (Darrow et al., 2009; Henry, 1988).

The main objective of this study is to investigate and quantify the impact of varying salt concentrations on soil freeze-thaw behavior, as well as the migration of moisture and salt within the soil. The research entails the utilization of NaCl salt, a commonly employed salt in varying proportions for road deicing operations, to examine its effects in one-dimensional freeze-thaw testing. The research will facilitate comprehension of the interconnected impacts of freezing point depression and osmotic suction on the soil properties and its susceptibility to frost heave after freeze-thaw cycles. The study will help in the efficient utilization of salts in road deicing practices.

METHODOLOGY

The soil used in this study was obtained from Ashville County, North Carolina. Laboratory testing was conducted to determine the index and engineering properties of the soil. The soil comprises 69.5% sand, 25.8% silt, and 4.7% of clay classifying it as silty sand (SM) based on USCS classification. The grain size distribution curve of soil is shown in Figure 1. The soil is classified as F3 (high frost susceptible) based on grain size distribution (U.S. Army Corps of Engineers, 1984). The soil properties are given in Table 1.

NaCl is the most widely used salt for road deicing operations in the USA (Cruz et al., 2022). Therefore, the salt used for the study was powdered sodium chloride (NaCl) with >99% purity. The specimens were prepared at four different pore water salinities i.e., 0% (DI), 0.2%, 1.0%, 5.0%. The selection of salinity levels is based on past studies and captures the effects of a large range of salinities.

The soil sample was oven-dried and passed through a #4 sieve to remove any coarse fractions. Saline solutions were prepared by mixing the required salt (NaCl) with deionized (DI) water to achieve the desired concentrations at the optimum moisture content of the soil given in Table *1*. The specimen with 0% salinity was prepared with DI water only. The prepared saline soil was compacted within a split mold measuring 14.6 cm in diameter and 15.2 cm in height. The cylindrical specimens were subjected to compaction in six layers using a standard proctor hammer, with a total of 33 blows in each layer. The specimens were compacted within a latex membrane to prevent any potential leakage that may occur following the insertion of thermocouples during the testing. Additionally, six acrylic rings measuring 2.54 cm in height were utilized to provide lateral restraint to the sample. Following the compaction process, the specimens were positioned above a base plate, which was linked to a Marriot cylinder serving as a water source, establishing an open system. The testing setup follows ASTM D5918 (retired). The specimens were not saturated for the current testing to prevent the potential redistribution of salt, which could occur as a result of its movement with water and subsequently alter the soil salinity along the vertical profile (Bresler, 1981).

After conducting freeze-thaw testing, the specimen was divided into six sections by height, and the moisture content of each section was determined. Following the determination of moisture content, the soil sample was used to assess the electrical conductivity (EC) of the soil. The EC of the soil was determined using the 1:5 soil-to-water ratio method (Sonmez et al., 2008). A mixture was prepared by combining 30 grams of oven-dried soil with 150 grams of deionized water, resulting in a suspension with a 1:5 ratio. The suspensions were manually agitated and subsequently left undisturbed for a duration of 24 hours (He et al., 2012). The suspension was also agitated 15 minutes prior to conducting the measurement of EC. The EC was measured using an EC probe that was linked to the Oakton PC700 meter. Equation 1 was utilized to determine the electrical conductivity of the saturated paste (SP) from 1:5 salt-water suspension (EC (1:5)) (Sonmez et al., 2008).

$$EC\ (SP) = 7.68 * EC\ (1{:}5) - 0.16 \quad (1)$$

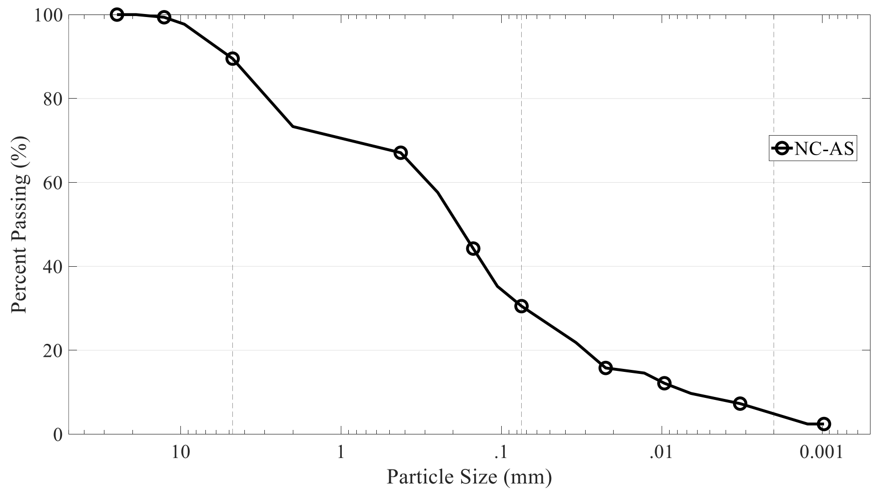

Figure 1: Grain size distribution curve of the soil

Table 1: Soil Properties

Soil Properties	NC-AS
Specific Gravity, Gs	2.63
Sand content (%) (2µm-4.75 mm)	69.5
Silt content (%) (75µm–2µm)	25.8
Clay content (%) (< 2µm)	4.7
Liquid Limit, LL	38
Plasticity Index, PI	NP
Saturated hydraulic conductivity (K_{sat}) (cm/s)	1.23×10^{-6}
Optimum Moisture Content (%)	19.2
Max. Dry Unit Weight (kN/m^3)	15.6
USCS Classification	SM
Frost Susceptibility Classification	F3

The freezing point depression (FPD) of the soil was assessed under similar salt concentrations and the soil's optimal moisture content using the cooling curve method. The saline sample was compacted within a test tube, up to a height of 2 cm. To measure the temperature of the soil, a thermistor with a negative temperature coefficient (NTC) was inserted into the soil. The thermistor was linked to a CR1000x data recorder to gather temperature measurements at regular intervals of 5 seconds. The test tube was submerged to a depth of 3 cm, 1 cm above the soil level, in a water bath maintained at a temperature of 0 ºC. The soil temperature was allowed to reach a state of equilibrium temperature. Subsequently, the temperature of the water bath was adjusted to -10 ºC. The temperature of the soil begins to decrease. The supercooled condition was of short duration, as the temperature rapidly increased to reach the true freezing point without any external stimulus. This was followed by the freezing of bound water and a subsequent decrease in temperature, resulting in the freezing of further bound water.

RESULTS AND DISCUSSIONS

Freezing Point Depression (FPD)

The inclusion of salt in soil has the effect of lowering the freezing point, resulting in a reduction of heave due to a decrease in ice segregation. The FPD of soils is predominantly influenced by the salinity of the pore water. However, the mineralogical composition and water content of the soils also have an impact on the FPD. Nevertheless, the impact of water content becomes insignificant when it reaches the critical water content, which is similar to the optimum moisture content of the soil (Shah & Mir, 2022b). Figure 2 displays the cooling curve utilized for the determination of the FPD for a pore water salinity of 1%. Figure 2 illustrates the freezing point depression (FPD) of 0.51 ºC at a salinity level of 1%. The FPD was measured at other levels of soil salinity i.e., 0%, 0.2%, 1%, and 5%. The corresponding FPD values were determined to be 0 ºC, 0.05 ºC, 0.51 ºC, and 2.96 ºC, respectively. As anticipated, the FPD exhibited a positive correlation with the elevated salt content. Previous studies have altered the freezing temperature of soil by reducing it to align with the freezing point depression (FPD) corresponding to the soil's salt concentration. However, it is crucial to acknowledge that the possible influence of salt on frost action could be mitigated. Hence, the present study does not lower the soil's freezing temperature to conduct a full evaluation of the overall impact of salt concentrations on the freeze-thaw behavior of soils.

The depth of frost penetration is crucial in determining the frost mitigation strategy (Sadiq et al., 2023). Many state agency frost protection guidelines recommend removing frost sensitive materials to more than 50% of the frost penetration depth. Figure 3 illustrates the depth of frost penetration in the soil. It is noteworthy to consider that the depth to which frost penetrates is contingent upon the temperature at which ice forms within the soil. Hence, the phenomenon of freezing point depression is considered in the calculation of frost penetration depth. As the salt concentration increases, there is a corresponding decrease in the frost penetration depth. As the salinity of the specimen increases, there is an increase in the quantity of unfrozen water present during the freezing process. The presence of unfrozen water content within soil exerts a substantial influence on the extent to which frost can penetrate. Increased amounts of unfrozen water present in the soil contribute to its thermal insulating properties, resulting in a delay in the freezing process and subsequently causing shallower depths of frost penetration. The depths of frost penetration at DI (0%), 0.2%, 1%, and 5% were determined to be 8.9 cm, 6.4 cm, 6.4 cm, and 3.8 cm, correspondingly.

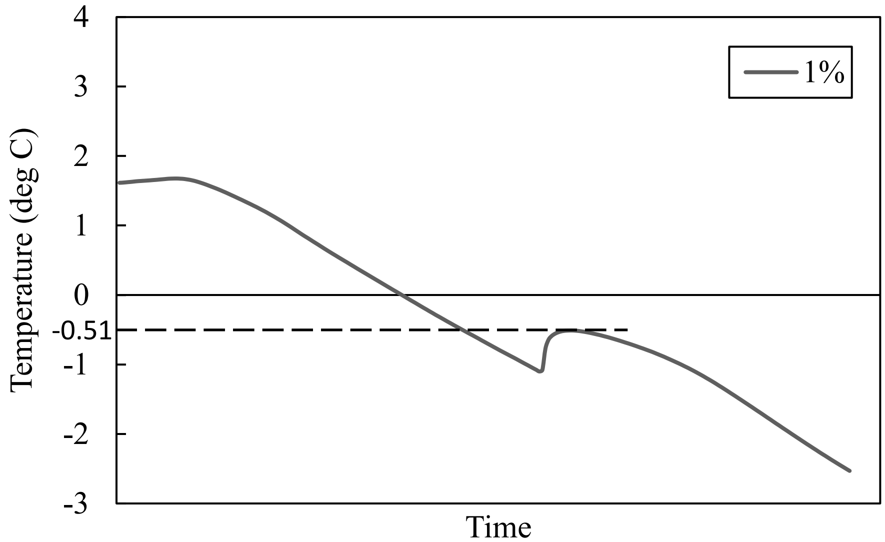

Figure 2: Freezing point depression curve obtained using the cooling curve method at 1% salinity.

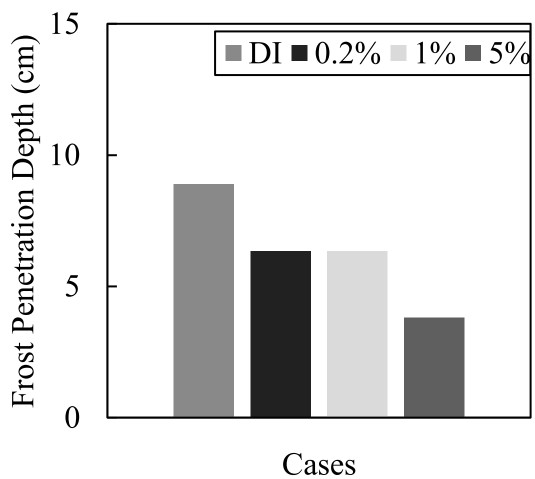

Figure 3: Frost penetration depth of the specimen in the second cycle

Total Heave, Heave Rate, and Heave Ratio

The measurement of the heave vs time curve of the soils during freeze-thaw testing was conducted with a laser displacement sensor, as depicted in Figure 4. The specimen undergoes heave during the freezing process and experiences settlement during the thawing process. As expected, the overall heave was higher during the second freezing cycle in comparison to the first freezing cycle. The specimens exhibit a significant heave in the first cycle in comparison to the second cycle. It has been noted that sandy soils exhibit substantial heaving in the initial cycle as opposed to later cycles, mostly due to their high hydraulic conductivity (Naqvi et al., 2023). As illustrated in Figure 4, there is a clear correlation between the increase in salt concentration and the reduction in heave. The measurements of the total heave for the cases with DI (0%), 0.2%, 1%, and 5% were determined to be 26.3 mm, 22.8 mm, 20.7 mm, and 18.0 mm, respectively. The magnitude of heave was observed to decrease by 13%, 21%, and 31% for salt concentrations of 0.2%, 1%, and 5% respectively, in comparison to the case with 0% (DI) salt concentration.

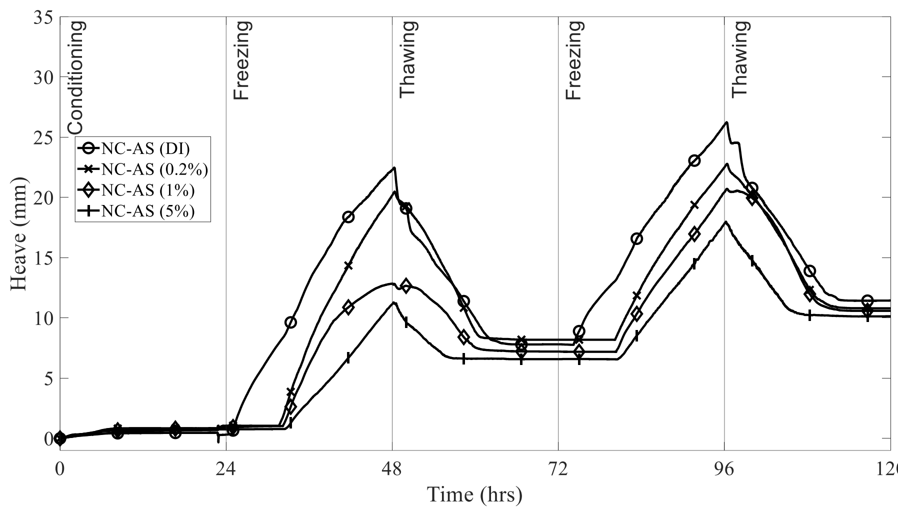

Figure 4: Heave vs Time curve during the freeze-thaw test.

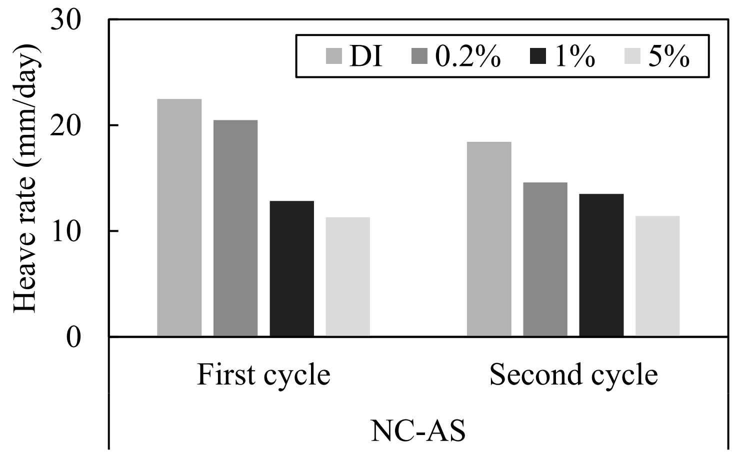

Figure 5: Heave rate in the first and second cycles during the freeze-thaw test.

The heave rate under varying salinity conditions was determined by taking into account a freezing period of 24 hours. The heave rate in both the first and second cycles is depicted in Figure 5. The heave rate reduces as the cycle increases, as illustrated in Figure 5. The primary reason for this is that the majority of heave in the case of sandy soils occurs in the first cycles (Naqvi et al., 2023). The heave rate decreases as salt concentrations increase, and the highest heave rate was observed at 0% (DI) concentrations with a magnitude of 22.5 mm/day. This was followed by heave rates of 20.5 mm/day, 12.9 mm/day, and 11.3 mm/day at salt concentrations of 0.2%, 1%, and 5% respectively during the first freezing cycle. The frost heave ratio in soils pertains to the expansion of soil volume or elevation resulting from the effects of frost action. The significance of this parameter is that it indicates the stability and integrity of the soil, as well as its ability to serve as an indicator of the anticipated infrastructure damage resulting from frost action. The frost heave ratio (ξ) is mathematically expressed as the division of the increment of frost heave (Δh) up to the frost depth (H_f) within a specific time period, as represented by equation 2. The highest heave ratio was observed at a salt concentration of 5%, exhibiting a magnitude of 26.6%. This was followed by salt concentrations of 0.2%, 1%, and 0%, which displayed heave ratios of 17.0%, 12.9%, and 11.9% correspondingly (Figure *6*). Hence, it can be inferred that while an increased concentration of salt results in a decrease in the overall amount of heave caused by freezing point depression, it still yields a high heave ratio that has the potential to cause substantial harm to infrastructure.

$$\xi = \frac{\Delta h}{H_f} * 100\% \tag{2}$$

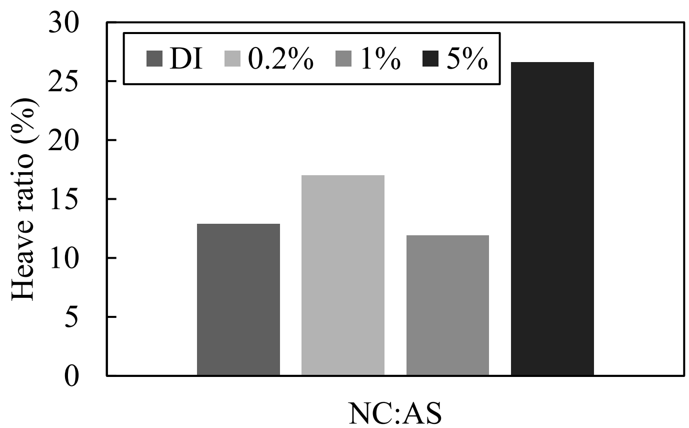

Figure 6: Heave ratio of soil after freeze-thaw test.

Water Intake and Moisture Content

Moisture movement in the soil is induced by the existence of a temperature gradient (Bing et al., 2015). The likelihood of ice lens development increases when water migrates towards the freezing front (Bai et al., 2020). The intake of water by soil is determined by the combined influence of matric and osmotic suction forces. The phenomenon of osmotic suction is a result of the concentration of salts in the pore fluid of the soil. The existence of salts in the soil can give rise to significant osmotic suction (Rao, 2019). Figure 7 illustrates the water intake quantity under frost action at varying salinity levels. During the freeze-thaw test, significant quantities of water were absorbed by all the specimens. The case characterized by a salt concentration of 0% (DI) exhibits the highest magnitude of heave, accompanied by the highest intake of 868 ml of water. This is followed by cases with salt concentrations of 0.2%, 5%, and 1%, which experience water intake of 776 ml, 741 ml, and 567 ml, respectively. The increased water intake of the 5% salt concentration in comparison to the 1% salt concentration can be attributed to the significant osmotic suction resulting from the presence of a larger quantity of salt. However, the total heave was higher at 1% concentration compared to 5% concentration as shown in Figure 4 because of less ice formation caused by higher freezing point depression in the case of 5% concentration.

The moisture content of the specimen at different depths following the freeze-thaw test is depicted in Figure 8. The variation in water content between the upper and lower portions of the specimen, as depicted in Figure *8*, clearly indicates the movement of water towards the freezing front. The moisture content is observed to be maximum along the height in the instance with 0% salt concentration, in comparison to cases with varying salt concentrations. The mean moisture content at various depths at 0% (DI), 0.2%, 1%, and 5%, was determined to be 33.5%, 28.8%, 29.6%, and 29.7% respectively. The lower average moisture content observed in saline soil (0.2%, 1%, and 5%) compared with non-saline soils (0%) can be attributed to a reduction in cryogenic induced suction resulting from a decrease in ice formation produced by the phenomenon of freezing point depression. When comparing the saline and non-saline situations, it becomes apparent that matric suction exerts a greater influence than osmotic suction at the above concentration during freeze-thaw. The calculation of moisture content uniformity within the specimen depth was conducted by determining the standard deviation of moisture content. The results indicated values of 3.4%, 4.0%, 3.8%, and 2.9% at concentrations of 0% (DI), 0.2%, 1%, and 5% respectively. In instances of saline soil, it has been observed that as the concentration of salt increases, there is a corresponding decrease in the variation of moisture content with respect to depth.

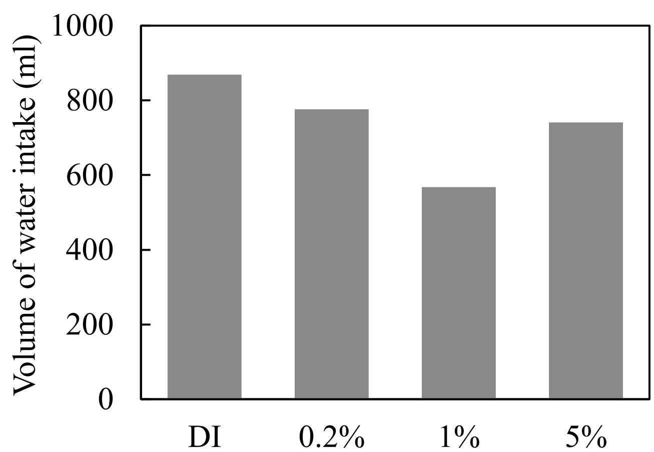

Figure 7: Total water intake by specimen at different salt concentrations

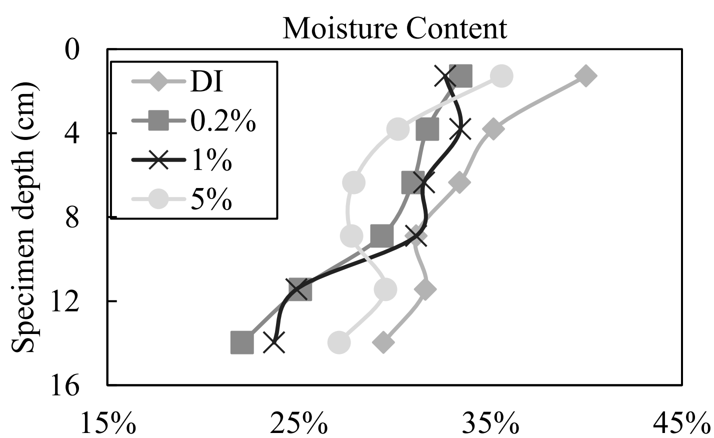

Figure 8: Moisture contents of the specimens along their depth for different cases after the freeze-thaw test

Salt Migration

The migration of salt towards the freezing front is attributed to the collective influence of freezing point depression, matric suction, osmotic suction, and the formation of ice lenses. During the formation of ice lenses, it has been observed that the ice expels solute because the ice is composed of pure water. As a result, there is a significant accumulation of salt at the freezing front. Osmotic pressure gradients may arise as a result of the difference in salt concentration between the freezing front and the underlying soil, leading to the movement of liquid water with salt toward the ice lenses. Furthermore, the phenomenon of salt migration occurs as water is transported towards the ice lens, driven by the process of matric suction (Bing et al., 2015; Wu et al., 2017). Figure 9 shows the saturated paste electrical conductivity (EC) of the specimen at various salt concentrations, as measured along its depth. The average electrical conductivity (EC) values of the soil were measured at 0%, 0.2%, 1%, and 5%. and were found to be 0.02 dS/m (attributable to natural salt content in the soil), 0.16 dS/m, 1.2 dS/m, and 5.59 dS/m accordingly. The migration of salt towards the top of the specimen is noticeable. The observed difference in salt concentrations between the upper and lower portions of the specimen was determined to be 0.03 dS/m, 0.48 dS/m, 3.70 dS/m, and 13.49 dS/m for the DI (0%), 0.2%, 1%, and 5% cases, respectively.

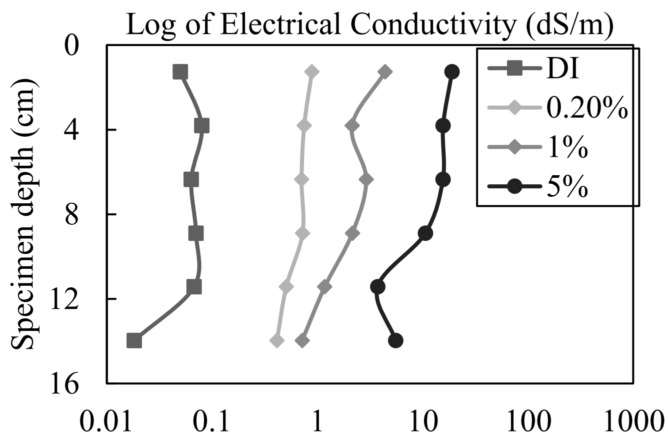

Figure 9: Electrical conductivity of the soil along the depth after freeze-thaw test.

CONCLUSIONS

Understanding the influence of salt concentration on the freeze-thaw behavior of soil is crucial in the preservation of infrastructure, the mitigation of expenses, and the minimization of the environmental impact associated with winter maintenance practices. It enables the formulation of enhanced and environmentally friendly approaches for addressing freeze-thaw occurrences in places characterized by cold climates. The current study aims to examine the impact of salt concentrations on the freeze-thaw behavior in soil. To understand the freeze-thaw behavior of the soil at different salt concentrations, a one-dimensional freeze-thaw test was carried out. In addition, the freezing point depression and the electrical conductivity test were conducted as well. The results of the study lead to the following conclusions.

- The FPD increased with higher salt levels, and greater salinity reduced frost penetration depth, as the presence of unfrozen water within the soil acted as thermal insulation, resulting in shallower frost penetration depths: 8.9 cm at 0%, 6.4 cm at 0.2% salinity, 6.4 cm at 1% salinity, and 3.8 cm at 5% salinity.
- The heave vs. time curve showed that heave is significantly higher during the first freezing cycle and decreases in subsequent cycles. An increase in salt concentration led to a

reduction in heave, with the highest heave reduction of 31% observed at 5% salt concentration compared to 0% (DI).

- All soils showed a significant water intake during the freeze-thaw test. Among the different salt concentrations tested, the soil with 0% salt concentration demonstrated the highest water intake (868 ml), followed by 0.2% (776 ml), 5% (741 ml), and 1% (567 ml) cases. This indicates a higher influence of cryogenic induced suction over osmotic suction during freeze-thaw.
- The moisture content of the soil exhibits considerable variability of up to 10.6% along the height of the specimen. Additionally, the moisture content in all cases is notably greater than the optimal moisture content of the soils at the beginning of the test, indicating substantial water migration within the soils.
- Varying salt concentrations with depth show salt migration towards the top of the specimen. Salt concentration variation between the top and bottom of the soils were determined to be 0.03 dS/m, 0.48 dS/m, 3.70 dS/m, and 13.49 dS/m for 0%, 0.2%, 1%, and 5% salt cases respectively. At 0%, 0.2%, 1%, and 5% salt concentrations, the average saturated paste EC values were 0.02 dS/m (natural salt content), 0.16 dS/m, 1.2 dS/m, and 5.59 dS/m respectively.
- At above salt concentrations, freezing point depression has a higher influence on osmotic suction. As a result, the presence of salt can help to mitigate freeze-thaw damage in soils.

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