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Scopus Compendex and Geobase Elsevier,
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Journals, Poland, Directory of Research Journals

International Journal of Earth Sciences and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume 09, No. 05

October 2016, P.P.2042-2047

The Frost Heave Property of Saline Soil in Western Jilin, China

YUANYUAN KONG[1], DONGGUO LI[2], QING WANG[1], CENCEN NIU[1] AND WENHUA WANG[2]
[1]*College of Construction Engineering, Jilin University, Changchun 130026, China*
[2]*College of Civil Engineering, Changchun Institute of Technology, Changchun 130012, China*
Email: *kongyy14@126.com*

Abstract: The paper presents frost heave experimental studies performed on the saline soil. The frost heave properties of soil are important for project construction in seasonal frozen area. The effects of initial water content and salinity on the frost heave properties are investigated, and the experiments on sodium carbonate saline soil indicate that the initial water content of the saline soil is mainly factor for frost heave, salt has inhibitory effect on frost heave, and the normal frost heave rate is proportional to the moisture content of soil. In addition, the study shows that the frost heaving stress is proportional to the moisture content of saline soil, and a high salt content can reduce the stress, and the frost heave stress and normal frost heaving ratio have a clear nonlinear relationship. Identifying the frost heave properties provides basic data support for the engineering construction in the seasonal frozen area, and is condutive to understanding the frost heave mechanism of saline soil.

Keywords: *seasonal frozen area; saline soil; high sodium salt; frost heaving ratio; frost heave stress*

1. Introduction

Soils suffer freeze-thaw during part or all of the winter at higher latitudes. In China, the distributions of seasonal frozen soil and saline soil occupy 55 and 2 percent of the total land area, respectively [1]. High-sodic saline soil is widely distributed in the Western Jilin, China [2]. And due to the chemical and physical properties of saline soil, salt migration not only seriously curbs the development of farming and animal husbandry in these areas, but also damage to engineering construction.

In saline soils, ions mainly exist in moisture and transfer with water. Under the freeze and thaw action, the air temperature catastrophe causes soil internal structure a staged irreversible damage. When the soil temperature falls to the freezing point of a salt solution, the water molecules will be precipitated in the form of pure crystalline ice, which means that in the process of phase change between water and ice [3]. When the temperature is below the freezing point, the water converts into ice, so frost heave occurs.

The frost action in engineering construction is caused by the coupling of solid, liquid, gas and heat in the porous medium [4]. Reports in the literature are mixed about the effects of freeze-thaw, most clay soils can become fissured and jointed, because uneven stress appeared in the soil during the freeze-thaw process, especially the soil with high salinity content, both the frost heaving and salt expansion can change its structure [5-6]. The change of temperature causes the transformation between ice and water, frost heave and thaw subsidence phenomena constantly appear, which induce a series of engineering problems. Salt expansion and frost heave will cause uneven swelling and cracking of roads, channels and airport runways, thus decreasing the stability of engineering structures [1, 7]. It is necessary to carry out the experimental research on frost heave properties.

This paper investigates the frost heave properties of sodium saline soil. After investigating distribution of saline soil in the study area, the vertical distribution of soil water and salt was obtained, the saline soils with different salt and moisture content were configured for frost heave test. The objective is to obtain normal frost heave ratio and frost heaving stress through the indoor frost heave tests. It is helpful for understanding the frost heave properties of sodium saline soil and studying the influence factors, and finding out the relationship between the normal frost heaving ratio and frost heave stress.

2. Study Area

2.1. Sampling Position

Jilin province, in the hinterland of Songliao Plain, is a typical seasonal frozen region, there distributes large area of saline soils in range of frozen depth exposed to periodic freeze-thaw each year. In western region, there distributes a large area of porphyritic saline soil. Because of snowmelt infiltration, the soils always have high moisture content in seasonal freezing zone.

The maximum freezing depth of the study area can reach 1.69m, in winter the lowest air temperature is about -36.5℃, winter time is generally up to five months. The sampling position is near the Sihe village in Nong’an county, Jilin province (44°22.717' N, 124°58.070' E). Figure 1 is the sampling position, and obviously the grassland has been degraded a lot. The surface soil presented white.

Figure1. *The saline soil sampling position in Nong'an County, Jilin Province*

2.2. Seasonal Evolution of Water and Salt

All tests were performed in accordance with the "Rules of Geotechnical Testing" (GB/T 50123-1999).

Actually the soil salinity of Nong'an County tends to be bigger in nearly fifty years, and the acreage of mild salinization land increased a little, the earlier data shows its salt content is just 0.1 ~ 0.3 percent in the 1980s, and rarely more than 0.5% [8]. The maximum sampling depth of saline soil is 40 cm in 2013 and 150 cm in 2014. The objective is monitoring the salt content in shallow soil, and further investigating whether the soil salinity transferred from the deep soil.

The research obtained water and salt contents presenting seasonal distribution given in Fig. 2 and Fig. 3.

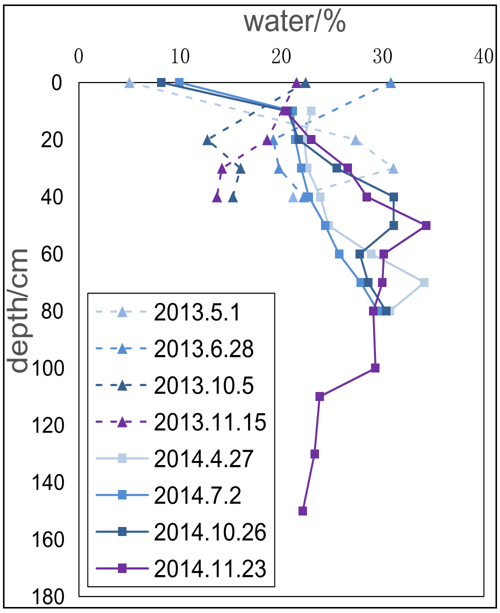

Figure2. *Seasonal moisture variation in saline soil*

Winter is the salt latency, the soils had a high salt content in this stage (Fig. 3), and soil experienced desalting process in summer. The total salt content in 2014 was higher than that in 2013 on the whole.

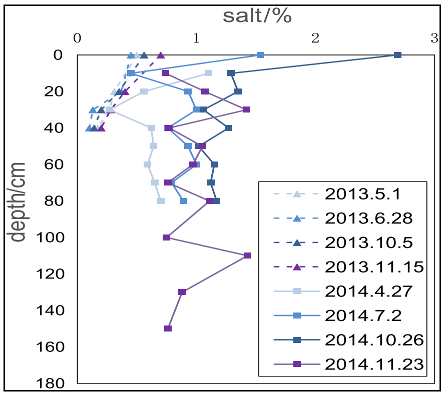

Figure3. *Seasonal salt variation in saline soil*

3. Testing Methodology

3.1. Frost Heave Test Method

As shown in Fig. 4, the normal frost heave ratio test used the program type high and low temperature test chamber, The measuring accuracy of temperature is within ± 0.1℃, the control range of temperature is - 40~120℃. The machine can be programmed to control the temperature and time, different temperatures to maintain the required time; can enter the next stage of the temperature. When the temperature kept at a certain temperature for a certain time, the instrument can enter to the next temperature stage automatically.

Figure4. *The frozen-heave factor test instruments*

The frost heaving stress test was carried out through the adjustable temperature mechanical testing machine (Fig. 5). The temperature range is from - 20℃ to 60℃, the precision of controlling temperature is ± 0.1℃. The loading range is 0 ~ 30 KN or 0 ~ 100 KN, the loading precision is 1N. The load-adding test process is controlled by a microcomputer, by which the test data and result can automatically draw.

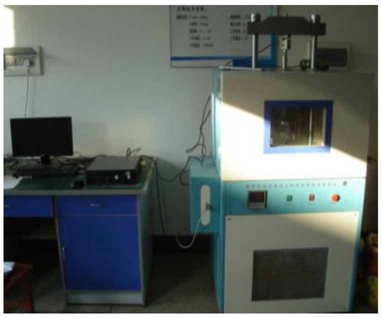

Figure5. *The frost heave force test instruments*

3.2. Sample Preparation

The normal frost heave ratio test and frost heaving stress test used the soil of depth 0.8 m. According to the soil property of the study are, the experiment prepared the specimens following a certain moisture and salt content as shown in table 1, the salinity mainly contained sodium carbonate in sampling position. For the purpose of accuracy analysis, the research leached the original salt out from the soil, and just added the sodium carbonate into the soil as test specimens.

According to the compaction degree of project construction, the specimens were compacted as it of 0.95. The aim was to finding the influent mechanism of soil moisture and salinity in the frost heave experiments.

Table 1: *The parameters of soil in the test*

Compaction degree	Salt content/%	Water content/%
	0.95	16
0.95	1.5	20
	2.0	24

3.3. Experimental apparatus and testing procedures

The normal frost heave ratio test and frost heaving stress test were done follow the standard of 《MTT 593.2-2011 Experimental study on physical and mechanical properties of artificial frozen soil》[9] .

The normal frost heave ratio can be calculated as formula (1).

$$\eta = \frac{\Delta h}{h_0} \times 100\% \quad \text{........................ (1)}$$

Where: η - The frost heaving ratio, %; Δh - The frost heaving amount, cm; h_0 - Original specimen height, cm. The frost heaving stress can be calculated as formula (2).

$$\sigma_{fh} = F/A \quad \text{........................ (2)}$$

Where: σ_{fh} – The frost heaving stress at t time, MPa; F - The axial load of the soil specimen at t time, N; A - The cross-sectional area of specimen at t time, mm^2.

According to the table 1, the soil was made to specimens of 10cm in diameter and 5cm high. In the normal frost heave ratio test, all specimens were put into the inside diameter 10cm and 7cm high Plexiglas pipes. As shown in Fig. 4, was carried out follow the standard in the dilatometer. In the frost heaving stress process, the soil specimens were putted into the dynamometer, and the frost heaving stress test was carried out follow the same standard through the instrument in Fig. 5.

In the two frost heave experiments process, the temperature was set to 5℃ first, and the purpose is to stabilize the soil temperature. Then, the study observed and tested the frost heave properties in the temperature of -3℃, -7℃, -10℃, -15℃, -20℃, and recorded the normal frost heave amount and stress under different temperature.

4. Test result and Discussion

4.1. Frost Heave Test Result

The experiments on the frost heave of sodium carbonate saline soil were carried out using the methods above. The experimental results, shown in Fig. 6 - Fig. 8, indicate that when the compaction degree of the soil is constant, the frost heave ratio increases as the water content.

In the Fig.6, soils water content was 16%. When the salt content was 0.95%, a frost shrinkage phenomenon occurred during the initial period of soil freezing. With the increase of salt content, the frost heave ratio becomes positive, indicating that frost heave appeared in the soil. The frost heave ratio is small and no significant change with the temperature decrease.

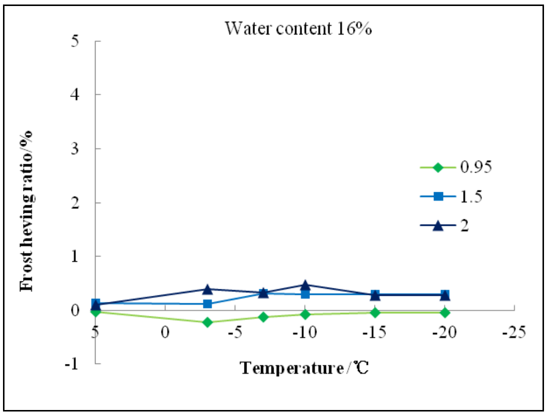

Figure6. *The frost heave ratio of soil with 16% water content*

In the Fig. 7, the water content was 20%. The soil with 0.95% salinity has a biggest frost heave ratio at temperature of -20 ℃, and a slight frost heave phenomenon appears at temperature of 5 ℃. With the increase of salt content, the final frost heave ratio becomes smaller, indicating that the salt and water contents decided the final normal frost heaving ratio.

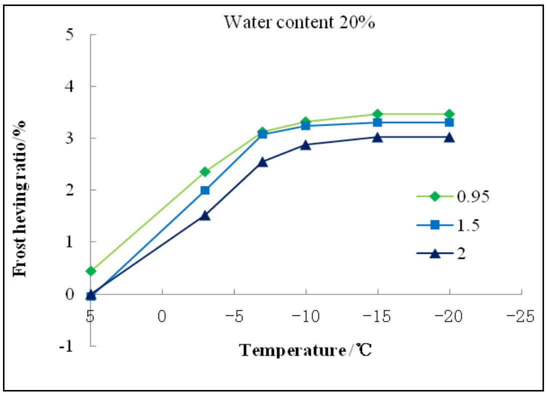

Figure7. *The frost heave ratio of soil with 20% water content*

In the Fig. 8, the water content was 24%. The final frost heave ratio was bigger than the specimens of 20% and 16% water content. When the water content kept steady, the normal frost heave ratio increased with the salinity decrease obviously. Compared to the Fig. 7, the increased water content leads to a larger frost heaving amount and faster frozen speed. The higher water content lowers the end temperature of frost heave process.

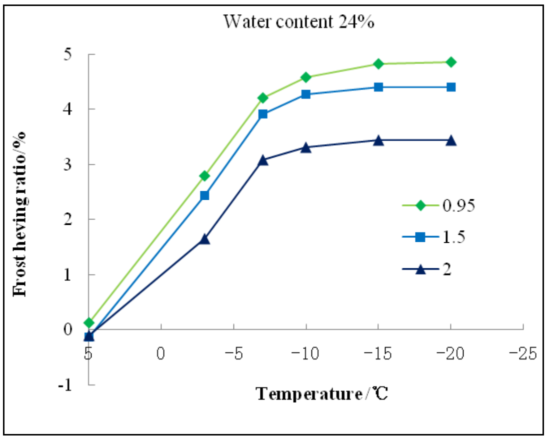

Figure8. *The frost heave ratio of soil with 24% water content*

The frost heaving stress test results are shown in table 2, when the water content is 16% or the temperature is 5 ℃, the soil frost heaving stresses were all 0 kPa. The frost heave process finished at about -15 ℃. With the decrease of temperature, the frost heaving stress increases gradually, the frost heaving stress is proportional to moisture content. The sodium carbonate effect the frost heaving stress complexly, the test result depends on the temperature, because the temperature affects the solubility of sodium carbonate and crystallization of sodium carbonate decahydrate.

Table 2: *The frost heaving stress of soil specimens/kPa*

Salt/%	ω/%	T/℃					
		5	-3	-7	-10	-15	-20
0.95	16	0	0	0	0	0	0
	20	0	40.1	91.1	106.4	134.4	134.4
	24	0	99.4	173.3	225.5	307.0	307.0
1.5	16	0	0	0	0	0	0
	20	0	61. 8	69.4	76.4	107.0	107.0
	24	0	119.8	188.5	211.5	256.7	256.7
2	16	0	0	0	0	0	0
	20	0	40.1	61.2	73.9	109.6	109.6
	24	0	113.4	155.4	187.9	249.7	249.7

According to the research achievements, it can be seen that there was functional relation between the normal frost heave ratio and the frost heaving stress. In this frost heave tests, the relationship was obtained in Fig. 9. And it can be represented with (3).

$$F = a\eta^{-b} \quad \text{......................} \ (3)$$

Where: F – The frost heaving stress, kPa; η- The normal frost heave ratio, %; a, b – The constant.

Because the soil specimens of 16% water content didn't have frost heave stress, so in the Fig.9 the paper just showed the 20% and 24% soil specimens. The water content is proportional to the frost heave stress, and the salt content is inverse proportion relation to the frost heave stress.

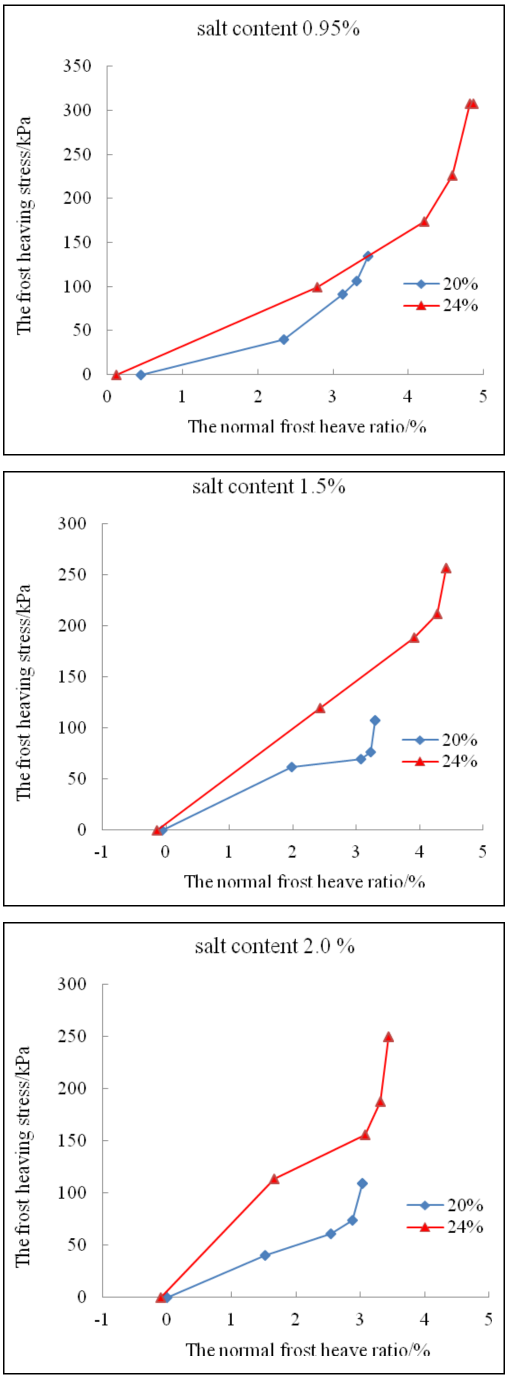

Figure9. *The relationship between the normal frost heave ratio and frost heaving stress*

4.2. Analysis and Discussion

According to the former researches, it can be seen when the salt content increases, the salinity concentration of the soil solution is higher, and the freezing temperature decreases as the concentration of the solution increases [1]. When the salt supersaturation occurs, the sodium carbonate crystals begin to precipitate according to the chemical equation (3), the salt crystals with ten crystal water are separated from the solution. The reduce in concentration of the sodium carbonate solution with the decreasing of the temperature, caused by the precipitation of crystals, leads to an increase in the freezing temperature of the soil. The frost heave process was complex due to the precipitation of salt crystals [10].

$$NaCO_3 + 10H_2O = NaCO_3 \cdot 10H_2O \ldots\ldots\ldots \quad (3)$$

The precipitation maximum supersaturation ratios are different for sodium carbonate saline soils with different initial concentrations. Analyzing the frost heave test, water and salt content decides the initial salt concentration. In general, the maximum supersaturation ratio increases, and it is difficult for sodium carbonate decahydrate crystals to precipitate as the initial concentration is decreasing. As the temperature decreased, the crystal growth rate in the soil decreased exponentially. The same salt content and cooling rate resulted in a same growth of salt crystals and salt expansion. Crystallization and salt expansion did not occur before frost heave in sodium carbonate saline soil [11].

The freezing process of soils can be divided into two stages, the first stage is the swelling deformation induced by the salt crystallization before soil freezing. The second stage is deformation caused by the moisture frost after soil freezing, including the segregative ice layers formation and the soil structure deformation induced by the soil particles displacement. The boundary temperature of the two stages is -4℃. At this point the soil has overcome the supercooling, began to freeze [12].

Analyzing the frost heave test results, the Fig. 7 and Fig. 8 show the soil expansion just occurred in the soil specimens of salt content 0.95%, indicating the salt crystallization is not obvious. The reason is that the clay content of the soil is very high and about 40%, resulting in the thickness of binding water film increasing. When the soil is too dense, the soil can expanse slightly under certain water content before frost heave. The sodium ions combine with the clay minerals, and it can increase the thickness of bound water in the soil. However, the bound water freezing temperature is lower than the ordinary free water. When the soil water content keeps constant and salt content increases, the normal frost heave amount would get down, due to the increasing of unfrozen water content affected by the sodium carbonate content [13].

In the Fig. 9, the curves of the soil specimens with 20% water content have turning point at the 3% normal frost heave ratio, when the temperature was lower than -7℃, the soil frost heaving stress increases significantly with the small increases of frost heaving ratio. And the soil specimens with 24% water content have a larger frost heave stress than the soil specimens with 20% water content. The test result indicates that the normal frost heaving stress increased rapidly in the second freezing stage.

5. Conclusions

The study obtained the frost heave properties of the Nong'an saline soil through frost heave experiments, the following conclusions were drawn from the above experimental results and analysis:

(1) This research obtained the water and salt seasonal evolution of saline soil vertical section in Nong'an County, Jilin province. Salinity of surface soil has a growing trend in recent years, and the evaporation depth of the area is about 30cm. The soil desalted in spring and accumulated salt in autumn.

(2) The water content is the main influence factor in the frost heaving ratio test, the critical water content of frost heaving is > 16%. The normal frost heave rate is proportional to the moisture content of soil. When the water content is constant, the salt has inhibitory effect on frost heave, and the effect would increase with the enhanced moisture content.

(3) The frost heave stress is proportional to the moisture content of saline soil, and a high salt content can reduce the stress. The frost heave stress and normal frost heaving ratio have a clear nonlinear relationship. The frost heave stress kept constant at -15 ℃ temperature, when the temperature was lower than -7℃, the frost heaving stress increases significantly with the small changes of frost heaving ratio.

(4) The study discovered the clay content induced soil expansion of Nong'an saline soil before the soil freezing, and salt expansion induced by sodium carbonate crystallization is not obvious.

Acknowledgements

This work was supported by the State Key Program of National Natural Science of China (Grant No. 41430642), Natural Science Foundations of China (Grant No. 41372267, 41402243, 41302247), and the Doctoral Scientific Fund Project (Grant No. 20120061110054).

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