

Article

A Study of the Insulation Mechanism and Anti-Frost Heave Effects of Polystyrene Boards in Seasonal Frozen Soil

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Abstract: The damages resulting from frost heaving are the main causes of channel destruction in seasonal frozen soil regions. Over the years, many experimental studies have been performed regarding the channel anti-frost heaving in the Hetao irrigation area. However, there have been few experimental research studies conducted regarding the insulation and anti-frost heave effects of polystyrene boards (EPS) of different thicknesses. Therefore, in order to explore the insulation mechanism and anti-frost heave effects of precast EPS laid under the conditions of different thicknesses, an anti-frost heave test field was established in the Hetao irrigation area for the examination of the ground temperatures, frozen depths, frost heave amounts, and water content change rules. This study's results showed that, for the laid EPS with thicknesses between 2 and 12 cm, the frost-heave reduction rate ranged from 53.2% to 92.6%; total accumulated temperature warming ranged from 248.65% to 565.93%; and the frozen depth reduction rate was between 59.8% and 75.9%. It was determined that the EPS per cm additions could effectively improve the ground temperatures at a buried depth of 30 cm by 0.78 °C, and reduce the frozen depth by 10.1 cm. Then, by comprehensively considering the positive economic and insulation effects, it was determined that the most appropriate thickness of the EPS laid under the precast concrete slabs in the Hetao irrigation area of Inner Mongolia was 8–10 cm.

Keywords: polystyrene; thermal conductivity; insulation mechanism; channel frost heave

1. Introduction

The Hetao irrigation area of Inner Mongolia has the characteristics of a temperate continental arid and semi-arid climate zone, where the winters tend to be long and cold, resulting in seasonal frozen soil. In regard to the freezing and thawing processes of the foundation soil, the freezing usually occurs in mid-October, and the thawing in late May of the following year, forming a freezing-thawing cycle. The channel foundation soil is considered to be strong frost heave soil, which is dominated by loam and silty loam. Due to the influences of the fluctuations in temperature, characteristics of the soil, groundwater levels, and other factors, combined with the negative temperature effects, the Hetao irrigation area has become an area with strong frost heaving. Also, due to the negative temperature effects, and under the conditions of no anti-frost heaving protective measures in the concrete board-line channels, after several alternately repeated freezing-thawing cycles, the lined channels and anti-seepage engineering measures which exist in the irrigation area have been damaged

to varying degrees. Furthermore, all of the channels show serious frost heaving damages. On the concrete faces of the channel linings, major damage phenomena have occurred, such as overhead and uplift movements with local collapsing. Each year after the freezing and thawing cycle, substantial amounts of manpower and funds are required for maintenance and reconstruction processes, which not only increases the difficulties and expense rate of the engineering management maintenance, but also affects the channel's anti-seepage effects and service life.

The use of laid EPS under-lining bodies for anti-frost heave measures has been successfully applied in countries such as Japan and Canada. Also, massive experimental research applications have been conducted in Beijing, Hebei, Shandong, Inner Mongolia, Ningxia, Heilongjiang, and other regions of China. According to the experiences of Canadian engineering departments [1], the laying of 1 cm thick EPS has the insulation effects equivalent to soil layers with 14 cm thicknesses. Furthermore, EPS measuring 6 cm in thickness can reduce the frozen depth by 50% or more [2]. Guo [3] used ANSYS software to analyze the change laws of the temperature, stress, and displacement fields under different thicknesses of EPS laid in the channel of the Hetao irrigation area of Inner Mongolia. Li [4] carried out EPS channel anti-seepage testing in Xinjiang. The results indicated that when EPS was used for heat preservation in the channels with higher underground water tables, the uplift pressures were large, which was prone to destroy the lining layers. In the channel conducted experiments performed by Liu et al. [5], it was proposed that 1 cm thick EPS could effectively improve the shady-slope ground temperatures of channel bases by 1.2 °C, and the sunny-slope ground temperatures by 0.7 °C. Song and He et al. [6] established a corresponding insulation board thickness calculation formula using the theory of heat conduction and a thermal resistance equivalent principle. Then, using the calculation formula, they proposed an optimal structural pattern for the insulation and anti-frost heave effects of concrete-lined channels. Li et al. [7] concluded that a simple and practical related analogy method and equivalent thickness method could be used to analyze the calculation methods of the insulation board thicknesses in different regions. The acquired test data from the Hebei Section in the middle route of the South-North Water Transfer were used for verification and correction purposes. However, the possibility that reserved frozen soil existed was not considered, which would potentially lead to high cost expenditures. Guo and Wang et al. [8] used ABAQUS finite element software to simulate the change rule of the anti-frost heaving force for EPS lined channels, and proposed the flexible utilization of EPS. Meanwhile, in the cases of frost heave effects in the channels, it was found that insulation boards had certain buffer and stress release effects, which tended to lead to more even stress distributions in the lined channels. Zhang [9] discussed the advantages of C20 precast concrete slabs and the EPS lined channel for the Shuangta main channel from the three aspects of economy, technology, and anti-frost heave effects.

In the research of anti-frost heave mechanisms conducted by Everett [10], the first frost-heave capillary theory was proposed. However, the proposed capillary theory was unable to explain how discontinuous ice lenses were formed. Also, this theory underestimated the frost heave pressure in fine-grained soil. Therefore, based on the aforementioned first frost heave theory, Miller [11] proposed a second frost heave theory to overcome the deficiencies of the capillary theory. In this second theory, it was believed that an ice margin with a low moisture content, low moisture conductivity, and no frost heave effects existed at the freezing front and the warmest ice lens bottom, which provided the basis for the establishment of a numerical model. Harlan [12] proposed a water-thermal coupled hydrodynamic model, and utilized a finite difference method for simulating the water flow and temperatures in the soil. This was found to be only suitable for one-dimensional moisture migration, and no calculation method for the soil water potential had yet been presented. Wang et al. [13] proposed the change rules of water, heat, and displacement during the process of channel frost heave through the establishment of a channel model. Liu et al. [5] theoretically analyzed the insulation mechanism of benzene boards and calculated their economic application benefits in channel anti-frost heave situations. From the perspective of mechanics, Jiang and Tian [14] proposed that the overall upward lifting movements of firm-to-soft hybrid channel lined structures were mainly due to the

interactions between the upward frost heave deformations of the bottom linings of the channels, and the radial deformations of the slope plates. Wu and Wang et al. [15] discussed the application effects of EPS in the concrete-lined channel of the Ningxia Yellow River irrigation area. Li [16] performed mechanical testing on the concrete channels of active mold bags in large irrigation areas in order to analyze the change characteristics of the stress and strain in those areas. Zhang [17] used a finite element method for the numerical simulation of the trapezoidal channel of the Xinjiang Corps, with consideration given to the fact that the channel failure characteristics were dominated by a crack formed at the 1/4 to 1/3 part of the channel bottom along the channel line, and that the channel base presented an uplift phenomenon under uneven frost heave conditions. Liu and Wang et al. [18] applied Automatic Dynamic Incremental Nonlinear Analysis (ADINA) software to create a model of a lined channel with an “adaptive variable cross-section”. The study results showed that the channel with an “adaptive variable cross-section” reduced the maximum normal frost heave quantity by 55.11%; the maximum normal frost heaving force by 51.65%; and the maximum tangential freezing force by 56.85%. Li and Fei et al. [19] analyzed the U-shaped channel anti-frost heave mechanism by using a thin shell structure theory. It was considered that the main reasons for the U-shaped channel damage were the negative influences of soil moisture in the channel base and the adverse weather conditions, which resulted in destructive uneven frost heave conditions in the channel. Hao et al. [20] proposed that the optimal insulation board thickness for the Hamatong irrigation area in Heilongjiang was 10 cm, and that 12 cm was the ideal thickness for the channel bottom. It was determined that when the optimal slope coefficient of the trapezoid channel was 2, the project costs were relatively low. Liao and Liu et al. [21] presented a new type of integrated anti-seepage insulation composite structure with a strong anti-seepage and anti-scouring ability, along with remarkable insulation and anti-frost heaving effects, a reasonable structure, good stability, and reliable operation. However, the construction of the proposed structure was more complicated. Zhu [22] believed that the plastic flow could only occur when the stress was greater than the long-term strength, and the total strain rate was decomposed into attenuation creep strain and non-attenuation creep strain rates. Then, by considering this theory, a constitutive model could be established which was suitable for the static load reaction temperature effects. Shen Mu et al. [23] proposed three field-coupling problems of water, temperature, and stress fields, and presented a simple coupling model. Shen et al. [24] considered that the uneven frost heaving of lining boards due to shear and foundation soil was the main factor related to frost heaving damages in trapezoidal channels with concrete precast slab linings. The restrictions on the sizes of the lining boards have led to very small internal stresses on the boards. Therefore, fracture damages generally do not occur. Song and Yu et al. [25] presented applications of SBS modified asphalt waterproof coiled material, along with APP modified asphalt waterproof coiled material, in channel lining projects in order to improve the stability and strength of the channels. However, the construction costs were found to be higher than those of other methods. Wang [26] conducted prototype observational experiments during the frost heaving processes of trapezoidal cast-in-site concrete channels with arc slope angles. Then, using the statistics of the test field temperatures, foundation-based soil moisture content, and channel observation point displacements, the frozen depths, rigid lining layer deformations, and stress change factors of the channel bed were analyzed. Zhang and He et al. [27] established a standardized structure for channel anti-seepage, insulation, and anti-frost heaving, and determined their application conditions and scopes. Also, they summarized an empirical method for the insulation board thicknesses, and a calculation method based on a thermal resistance equivalent principle, in order to propose the technical requirements for laying the insulation boards, and the control standards for the quality inspections. An, Xing et al. [28] used theoretical calculation methods to analyze the change rules of the tangential frost heave forces and normal frost heave forces. The results of their experimental testing indicated that the tangential frost heave forces were relatively axisymmetric to the center of the channel bottom, of which the numerical sizes showed approximate symmetrical distributions along the cross-sections. Due to the buffering actions of the benzene boards, the tangential frost heave forces became greatly decreased, in which the shady-slope

forces were observed to have been cut by 92.7%. In regard to the normal frost heave forces with the laid EPS, it was found that at other parts of the channel, the forces were cut by more than 80%, and those at the bottom of the channel were reduced by 94%. Zhang and Wang et al. [29] established a channel frost heave mechanics model which they combined with a finite element model. They then used an isotropic calculation to show that local normal frost heave forces existed in the upper shady-slope with a maximum value of 0.063 MPa. Meanwhile, the forces in the sunny-slope were very small, and mainly distributed in the upper part with a maximum value of 0.04 MPa. Liu and Ning et al. [30] believed that there was a relationship between the soil-ice elastic constants and those of the entire frozen soil mass at a certain temperature. On this basis, a damage mechanics method was applied in the research studies of the frozen soil mechanics in order to establish a frozen soil constitutive model which considered the soil mass damages.

At the present time, there have been numerous research studies completed regarding the frost heave mechanism of EPS lined channels. However, testing results regarding insulation effects and mechanisms, as well as suitable laying thicknesses, are still lacking. Meanwhile, there is no relevant research on the suitable EPS thickness, frost expansion mechanism, and water transport law under certain conditions in the Hetao area. At present, no heat preservation scheme for channels exists that is applicable to the Hetao area, and the problem of channel frost heaving has not been solved. Thus, in this study, the frost heaving amounts, frozen depths, ground temperatures, and ground water levels of EPS with different thicknesses were monitored. The anti-frost heave mechanisms of insulation boards laid under the conditions of precast slabs were also analyzed. Meanwhile, the suitable laying thicknesses of the EPS boards under precast concrete linings were discussed for the Hetao irrigation area, so as to put forward the heat preservation scheme of the channel under certain conditions in the Hetao area, analyze the main causes of frost heaving, and solve the regional frost heaving problem under certain conditions. The results of this study provided a scientific basis, demonstrations, and technical support for the future applications of EPS insulation boards with anti-seepage linings in the main channels of the Hetao irrigation area.

2. Materials and Methods

2.1. The Test Field

This study's test field was located from the 8 + 200 section in the southwest, to the second gate of the sub-main channel to the south of the Yongji irrigation district in the Hetao irrigation area. The annual average temperature in the study area was 6.9 °C, and the average relative humidity ranged between 40% and 50%. The multi-year average rainfall was 144.2 mm, which was characterized by large temperature differences, sufficient sunlight, and annual sunshine hours of 3100 to 3300 h. The test field consisted of a heavy silty loam geology, and was categorized as strong frost heave soil with frozen durations of approximately 180 to 240 days. The frozen index was from 536 to 3450 °C·d, and the frozen depths ranged from 70 to 120 cm.

2.2. Test Design and Observations

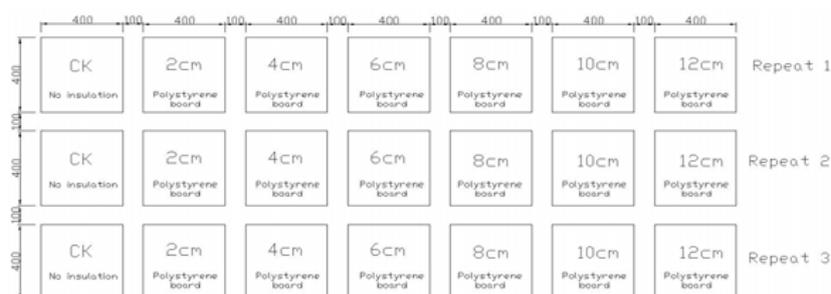
In this research study, different treatment blocks were set up in the test field in a test block area measuring 4 m × 4 m. A 6 cm thick precast concrete block was laid on top of the contrast section and insulation board, and a 3 cm thick M10 mortar pad was laid under the concrete slab. Each test block interval was 1 m. A total of seven EPS treatments were completed with thicknesses of 2 cm, 4 cm, 6 cm, 8 cm, 10 cm, and 12 cm laid, and no insulation treatments were conducted (contrast section). The specific design of the test process is shown in Table 1.

Table 1. Frost heave test processing design table.

Processing	Processing 1	Processing 2	Processing 3	Processing 4	Processing 5	Processing 6	Processing 7
EPS thickness (cm)	0	2	4	6	8	10	12
Processing #	Contrast section	A20-2	A20-4	A20-6	A20-8	A20-10	A20-12

The experimental observations mainly included the ground temperatures, frost heave amounts, soil moisture content, under-ground water table, and so on. The ground temperatures were observed by using a 18B20 temperature sensor (Digital Temperature sensor, 18B20, Bayannaer Yuanshuo Technology Development Co., Ltd., Bayannaer, China) with an observational precision of ± 0.5 °C, and the temperature acquisition depth was divided into five layers, each layer being 10 cm thick. Through the automated collection system and GPRS network, the monitoring, transmission, and storage of the geothermal data were completed with data collection intervals of 30 min. The base piling which was used to measure the frost heave amounts was embedded into the test field, and consisted of a four-scruple iron pipe and a coated six-scruple PVC plastic pipe. Grease was used to fill the space between the inner and outer pipes. The frost heave deformation amounts with the different heat treatments were observed by levels every five days during the freezing and thawing periods. The moisture content of soil at depths between 0 and 50 cm were determined by artificial borehole sampling. A drying method was used before freezing, during the maximum frozen depth, and after freezing and thawing, respectively.

In order to prevent the interference of boundary conditions on frost heaving, a 6 cm polystyrene board was vertically laid around each block, so as to reduce the surrounding heat exchange, guarantee 1D thermal motion, and reduce the influences of horizontal frost heaving deformation on the vertical deformation of the block. The ground temperature probe was buried 30 cm below the surface to analyze the variation rule of ground temperature in the same layer under different thermal insulation treatment conditions. A depth freezer was installed in the test site to measure the frost depth, with three repetitions for each processing procedure, for a total of 21 block processing procedures. The test block layout is shown in Figure 1. The measurement positions of frost heaving amount and soil moisture content are located in the middle of the test block. There was one measurement point of frost heave in each test block and three sampling points of soil moisture content, with spacing of 10 cm. The data used in this paper are the average values of three repeated test blocks.

**Figure 1.** Planar layout of different treatment blocks.

A polystyrene insulation board (EPS) is a plate-shaped geosynthetic material. In this study, by adding the former to a polystyrene polymer as a raw material, a polystyrene foam granule was formed. Then, after compressing, shaping, and cutting, the newly formed material was found to have the positive characteristics of a light weight, low thermal conductivity, low water absorption rate, high compressibility, high durability, and low cost [7]. Table 2 shows the mechanical properties of the EPS which were used in this experiment, as well as those properties required by the design specifications of the anti-frost heave in the channel construction (SL23-2006).

Table 2. Mechanical properties of the EPS.

Test Index	Density (kg/m ³)	Water Absorption Rate (Water Immersion for 96 h, Volume Percentage, %)	Compressive Strength (Compression 50) (kPa)	Bending Strength (kPa)	Size Stability, −40 °C to +70 °C (%)	Thermal Conductivity (W/(m·K))
Normative index	≥15	≤6	≥60	≥180	≤4	≤0.041
EPS test value	20	1.7	240	250	±0.4	0.036

3. Results and Discussion

3.1. Change Rule of the EPS to Reduce the Frost Heave Amount

Through the experiments conducted in this study, the change process lines of the frost heave amounts in foundation soil with different insulation treatments from November 2015 to April 2016 were obtained, as shown in Figure 2. The maximum frost heave amount of the foundation soil and the reduced frost heave amounts with the different EPS processing conditions are shown in Figure 3. The calculated reduction rates of the frost heave amounts using the different EPS processing procedures are specified in Table 3.

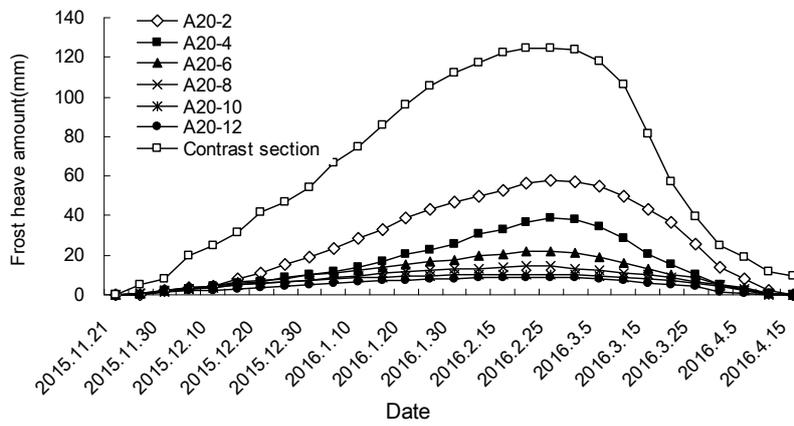


Figure 2. Change process lines of the frost heave amounts using different EPS treatments.

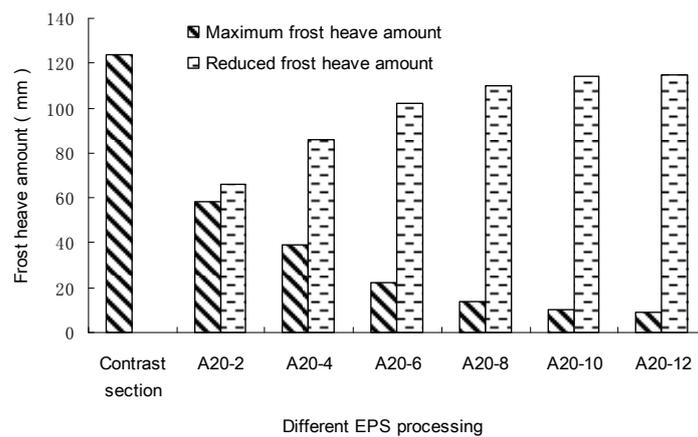


Figure 3. Maximum frost heave amount and reduced frost heave amounts with the different EPS processing procedures.

Table 3. Eigenvalue and reduction rates of the frost heave amounts of EPS insulation boards with different thicknesses.

Processing	Contrast Section	A20-2	A20-4	A20-6	A20-8	A20-10	A20-12
Maximum (mm)	124	58	39	22	14	10	9
Reduction amount (mm)	0	66	86	102	110	114	115
Reduction rate (%)	0	53.2	69	82.3	88.5	91.7	92.6

As can be seen in Figure 2, Figure 3, and Table 3, the frost heave amounts when the insulation measures were in place were significantly less than that when no insulation measures were used. Also, with the increases in the insulation board thicknesses, it was observed that the frost heave amounts successively decreased. For example, the reduction rates of the frost heave amounts with EPS boards between 2 and 12 cm in thickness ranged from 53.2% to 92.6%. These findings illustrate the extremely significant anti-frost heave effects of the EPS.

The relationship between the thicknesses of the EPS and maximum frost heave amounts was fitted by the measured maximum frost heave amount of the EPS with different thicknesses as follows:

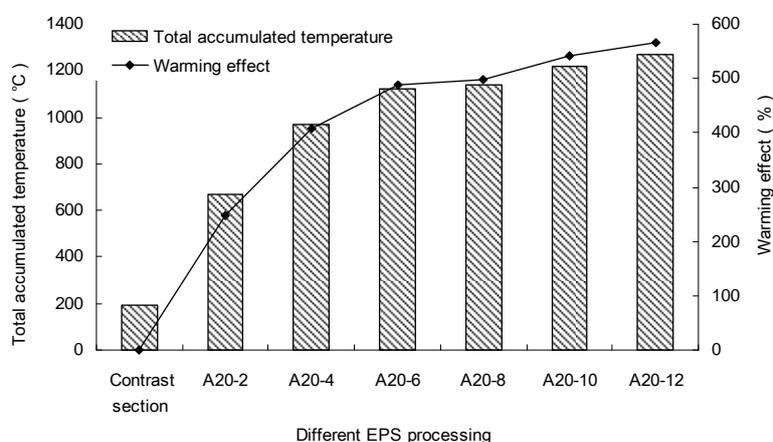
$$Y = 97.811e^{-0.2216X}, R^2 = 0.965 \quad (1)$$

In the equation, X represents the insulation thickness (cm) and Y denotes the maximum frost heave amount (mm).

In this study's results, the maximum frost heaving amount and the thicknesses of the EPS showed an exponential function relationship. It was observed that the former would decrease with increases in the EPS thickness, and the reduced size also became gradually smaller. When laying the EPS boards with thicknesses of less than 8 cm, it was determined that significant influences were evident in the frost heave amounts. Meanwhile, when EPS boards with thicknesses greater than 8 cm were laid, there were no significant effects observed in the frost heave amounts.

3.2. Change Rule of the Ground Temperatures under the Different EPS Thicknesses

In this study, through analyzing the ground temperature at the buried depth of 30 cm with EPS boards laid under precast slabs in the test field, the total accumulated temperature of the foundation soil, along with the warming effects during the observational period (November 2015 to April 2016), were calculated (Figure 4). The warming effect calculation method is shown as the total accumulated temperature of each processing procedure with the laid insulation board minus that of the processing procedure without the laid insulation board (contrast section), then divided by the latter, and multiplied by 100%.

**Figure 4.** Total accumulated temperature and warming effects of the EPS with different thicknesses.

The temperature extremum and temperature difference diagram of the foundation soil with different EPS processing procedures is illustrated in Figure 5.

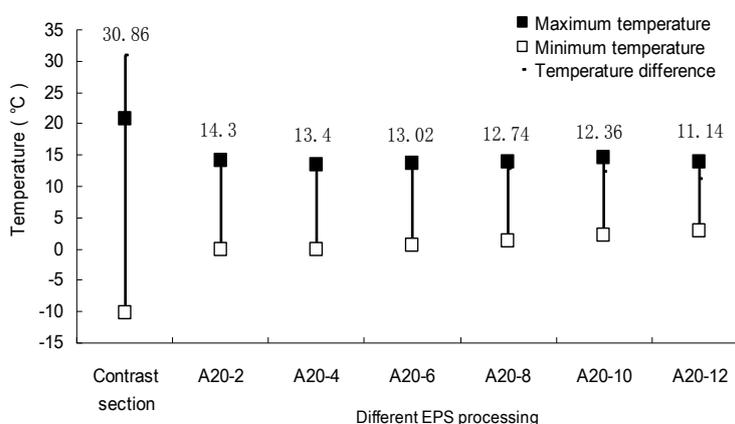


Figure 5. Temperature extremum and temperature difference values of the EPS with different thicknesses.

The observational period of this study’s test was 183 days, including 106 days of negative temperatures with no insulation measures in place. The ground temperatures with no insulation processing were negative on more than 50% of days during the observational period. However, no negative temperatures occurred when the insulation boards were laid during the observational period, which demonstrated the extremely significant warming effects of the EPS. In regard to the total accumulated temperature, with the 2 to 12 cm thick laid EPS, the temperatures reached between 248.65 and 565.93%, which further illustrated the extremely significant insulation effects of the laid EPS. When the laid EPS was between 2 and 8 cm in thickness, the warming effects were found to be the most obvious. At the same time, when the thicknesses were greater than 8 cm, the total accumulated temperature warming effects magnitude slowly increased with the increases in the insulation board thicknesses. It was thus recommended that the most appropriate thickness of the EPS laid beneath the precast boards was 8 cm.

Figure 5 shows that with the increases of the insulation board thicknesses, the temperature differences of foundation soil gradually decreased during the observational period, and the temperature difference in the contrast section reached a maximum of 30.86 °C. In the cases of 2 to 12 cm thick EPS being laid for processing the foundation soil, the temperature difference values were between 14.3 and 11.14 °C, and decreased by 53.6% to 63.9%. These findings confirmed that laying EPS could significantly reduce the temperature difference values during this study’s observational period.

Temperature observation involves recording one datum per hour, for a total of 24 data per day. These 24 data are then averaged to obtain the daily mean temperature. The observation period is 183 days, for a total of 183 data, followed by averaging to obtain the mean temperature during the observation period. In addition, the temperature increment values of each processing and insulation board per unit thickness are calculated. The calculation results are shown in Table 4.

As can be seen in Table 4, under the conditions of the precast concrete slabs, when EPS measuring 1 cm in thickness was laid, the ground temperature could be improved at a buried depth of 30 cm by 0.78 °C. Meanwhile, the thicker the laid EPS was, the less effective the warming effects of the insulation board in the unit thickness were observed to be.

Table 4. Warming effects of the EPS in unit thickness (at a buried depth of 30 cm).

EPS thickness	0	2 cm	4 cm	6 cm	8 cm	10 cm	12 cm
Mean temperature during the observational period (°C)	0.99	3.25	5.05	6.07	6.10	6.81	6.93
Warming (°C)	\	2.26	4.06	5.08	5.11	5.82	5.94
Warming of the insulation board in unit thickness (°C)	\	1.13	1.02	0.85	0.64	0.58	0.49
Mean warming of the insulation board in unit thickness (°C)	\				0.78		

3.3. Change Rule of the Frozen Depth under the Different EPS Thicknesses

Figure 6 shows the change process lines of the frozen depths of the foundation soil with different thicknesses of laid EPS, as well as the contrast section. Figure 7 presents the maximum frozen depth and reduced frozen depths of the EPS processing procedures with different thicknesses. It can be seen in Figure 6 that the foundation soil in the contrast section began freezing in mid-November and had reached a maximum frozen depth of approximately 75 cm by mid- to late January. The bottom section and the surface had begun to melt in early March and mid-March, respectively, and both were completely melted by mid-April. As can be seen from the change process lines of the frozen depths with the different thicknesses of EPS, the frozen depth differences between December and the following March were observed to be significant. The maximum frozen depth decreased with the increases in the thicknesses of the insulation boards, which indicated that the thicker the insulation board was, the smaller the frozen depth of the foundation soil would be.

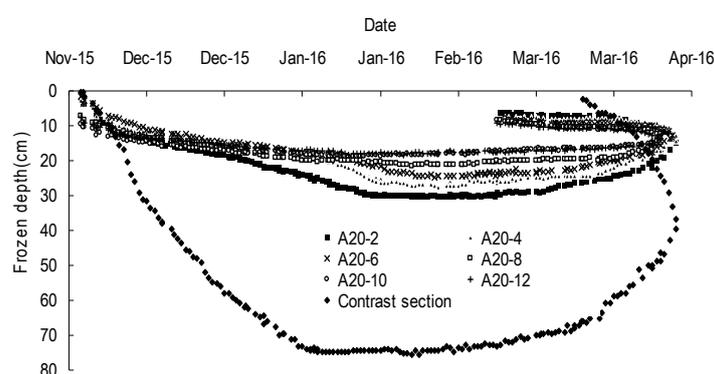


Figure 6. Change process lines of the frozen depths under the different EPS thicknesses.

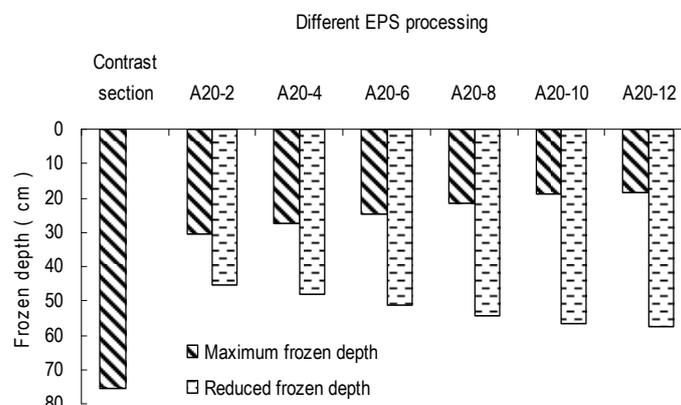


Figure 7. Maximum frozen depth and reduced frozen depths under the different EPS thicknesses.

The reduction rates of the frost heaving under the different EPS thicknesses and the reduced frozen depths for each cm of the EPS, were calculated in this study, as shown in Table 5. It can be seen from Figure 7 and Table 5 that the maximum frozen depth decreased with the increases in the insulation board thicknesses. Also, in the cases where no insulation measures had been taken, the maximum frozen depth of the foundation soil was 75.7 cm. It was determined in this study that when the EPS boards with thicknesses measuring between 2 and 12 cm were laid, the reduction rates of the frozen depths were between 59.8% and 75.9%. These observations illustrated the extremely significant reductions in the frozen depths when insulation measures were used. The reduced frost depth per unit thickness gradually decreased with the increases in the insulation board thicknesses, of which the average reduced frost depth per cm of EPS was found to be 10.1 cm. In summary, it was found that the anti-frost heave effects of the EPS were extremely significant in this study’s experimental tests. It was

thereby concluded that the EPS could effectively reduce the frozen depths of the channel in the study area when applied during the channel lining engineering process.

Table 5. Reduction rates of the frozen depths under the different EPS thicknesses and the reduced frozen depths for each cm of the EPS.

EPS Thicknesses	0	2 cm	4 cm	6 cm	8 cm	10 cm	12 cm
Maximum frozen depth (cm)	75.7	30.4	27.4	24.6	21.4	19.0	18.2
Reduction rate of the frozen depth (%)	\	59.8	63.8	67.5	71.7	74.9	75.9
Reduced frozen depths for each cm of the EPS (cm)	\	22.7	12.1	8.5	6.8	5.7	4.8
Average reduced frozen depth for each cm of the EPS (cm)	\	10.1					

3.4. Insulation Mechanism of the EPS

Moisture redistribution phenomenon is known to occur during the freezing process of soil which is sensitive to frost heave. The phenomenon has been observed to be mainly presented as moisture in the lower soil migrating to the freeze front, where ice interlayers are formed. This redistribution tends to lead to increases in soil volume, which is then shown as surface soil frost heaving on the macro level. Under the same freezing conditions, the soil properties and groundwater levels will determine the amount of water transfer during the freezing process.

The soil moisture content with no insulation processing (contrast section) was measured with soil sampling. The sampling position was located in the middle of the test block, and three samples were taken in parallel on the same layer with a sampling-point spacing of 10 cm. The sampling time is the period before freezing, the maximum freezing period, and the period after melting. The sampling depth was 0–50 cm, with 10 cm for each layer.

The software of Golden Software Suffer (Suffer, 11) was used to prepare the distribution map of soil moisture content on the 0–50 cm soil layer in three different periods on the platform without thermal insulation processing (contrast section), as shown in Figure 8. In this figure, the horizontal axis is the distance from the sampling point, and the vertical axis is the depth of the soil profile. Due to the fact that the measured data consist of three parallel samples in the same layer, the distribution results of the soil moisture content in the soil profile drawn by Suffer, 11 software are highly reliable and representative.

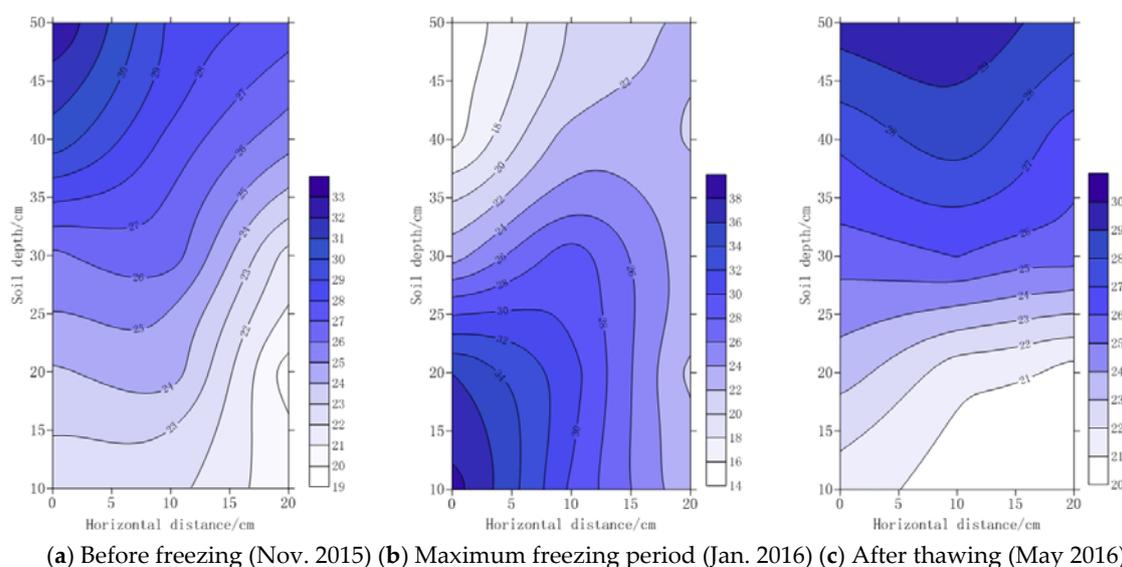


Figure 8. Changes in soil moisture content distributions.

It can be seen from Figure 8 that, during the freezing process (before freezing and freezing period), the moisture content of the 10 to 30 cm soil layers increased, while that of the 30 to 50 cm soil layers decreased. These findings indicated that, during the freezing, the moisture migrated from the soil beneath a depth of 30 cm to the upper layers. In other words, during the process of the freezing of the soil, the moisture migrated to the freeze front. During the thawing process (freezing period and after thawing), the moisture content of the 0 to 30 cm soil layers decreased, while that of the 30 to 50 cm soil layers increased, which indicated that the moisture of the 0 to 30 cm soil migrated to the lower soil layers during the thawing process. Also, the surface uplift movements and frost heaving deformations gradually decreased.

The average soil moisture contents of 0–30 cm and 30–60 cm were calculated under three conditions of no thermal insulation (contrast section), laying a 2 cm polystyrene board, and laying a 4 cm polystyrene board. Table 6 shows the migration values of the moisture content in the 0–30 cm and 30–60 cm soil layers under the three different treatments before freezing, during the freezing period, and after the thawing process had occurred. The migration values of the water during the frozen period without the thermal insulation treatments were observed to be the largest. The moisture migration values with no insulation processing during the freezing period reached the maximum. It was found that the moisture transfer values became gradually smaller with the increases in the thicknesses of the insulation board. The results indicated that the laying of the EPS insulation board effectively reduced the moisture migration to the freezing front, and the thicker the laid insulation board was, the smaller the observed moisture migration amount would be.

Table 6. Moisture changes in the 0 to 50 cm soil layers under the different EPS thicknesses.

Processing	Soil Depth (cm)	Initial Moisture Content (%)	Migration Rate during Freezing Period (%)	Migration Rate during Thawing Period (%)
Contrast section	0 to 30	23.75	+57.4	−25.8
	30 to 50	29.75	−40.8	+47.6
2 cm-thick EPS	0 to 30	26.6	+13.6	−22.9
	30 to 50	28.5	−15.7	+4.9
4 cm-thick EPS	0 to 30	20.4	+7.7	−16.7
	30 to 50	24.8	−10.1	+3.67

Note: The migration rate equals the moisture content during the freezing period (thawing period) minus the initial moisture content; “+” and “−” denote the upward and downward moisture migrations, respectively.

The heat during the process of channel frost heaving existed in the form of conduction. The atmosphere conducted the heat to the channel, and then the channel conducted the heat to the channel foundation soil. The frost heaving occurred in the study area when the soil, heat, and moisture reached the frost heaving conditions. According to the measured data, the thermal conductivity of the concrete was $2.33 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, and that of the sandy loam was $1.1 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$. Meanwhile, the thermal conductivity of the EPS was only $0.04 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, which was only 1.7% that of the concrete, and 3.6% that of the sandy loam [6]. The principle for the application of the EPS insulation was to use EPS with a low coefficient of thermal conductivity for the lining between the channel and the soil, in order to prevent or decelerate the transfer of heat and migration of moisture in the channel foundation soil. Also, the water-thermal coupling in the frozen soil would become weakened, resulting in effective insulation conditions, and the reduction of heaving deformations in the channel foundation soil.

The EPS linings in concrete channels could potentially significantly reduce the frozen depths in the channels. It was observed that the thicker the EPS was, the smaller the freezing depth would be. However, when the thicknesses of the EPS reached a certain value, the frozen depths were observed to no longer display significant changes [31]. The thicknesses of the EPS displayed significant influences on the heaving amounts, temperatures, and frozen depths of the base soil. The frost heave amounts consistently decreased with the increases in the thicknesses of the EPS in the channel. However, the range became continuously smaller. Therefore, it was recommended in this study that

choosing the most economical and reasonable thicknesses of the EPS would play a key role in reducing the construction costs of installing insulating lining in channels in the future [3].

4. Conclusions

In this research study, through observations of a complete freezing and thawing period, the observed data were analyzed in order to obtain the following main conclusions:

(1) For the laid EPS with thicknesses ranging from 2 to 12 cm, the reduction rates of the frost heave were from 53.2% to 92.6%; the total accumulated temperature was between 248.65% and 565.93%; and the reduction rate of the frozen depths ranged from 59.8% to 75.9%. These results illustrated the extremely significant insulation and anti-frost heave effects of the EPS. Then, through comprehensively analyzing the influences of the EPS thicknesses on the frost heave amounts, frozen depths, and ground temperatures, the most appropriate thickness of the laid EPS under the precast concrete slabs in the Hetao irrigation area of Inner Mongolia was determined to be 8 cm. The results of the experiment were obtained under typical climatic conditions in this region. If special cold conditions were to exist, this would be increased by 2 cm, on a basis of 8 cm. Therefore, it is recommended that the suitable thickness of polystyrene boards in the Hetao area is 8–10 cm.

(2) In this study's experimental testing results, it was observed that the warming and frost depth reduction effects of the EPS per unit thickness were significant. It was found that each additional cm of EPS could improve the ground temperatures at a buried depth of 30 cm by 0.78 °C, and also reduce the frozen depth of the foundation soil by 10.1 cm.

(3) The main cause of frost heaving in the channel foundation soil is the migration of moisture from the 30 to 60 cm soil layers to the upper soil during the freezing period. This migration leads to a redistribution of the soil moisture, formations of ice interlayers, and increases in the soil volume.

(4) The EPS with a low coefficient of thermal conductivity was determined to have the ability to prevent or decelerate the heat transformation of the channel foundation soil, as well as effectively prevent moisture migration on the freezing front, inhibit the redistribution of the soil moisture, weaken the water-thermal coupling in the frozen soil, and provide positive insulation effects.

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