Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2022, 9(11):141-151**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Experimental study on lateral moisture migration of soil under artificial freezing conditions

Du dongdong[1]

[1]School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo Henan 454100, China

Abstract In this paper, the pollution clays under different freezing temperatures were studied by artificial freezing tests, and the power consumption, the amount of liquid recharging during freezing, the amount of liquid recharging during freezing, and the variation rules of the temperature field and water field during freezing were obtained. And we get the following conclusion: (1) The temperature of the part within 5cm of the frozen plate decreases rapidly and greatly, with a temperature decrease of 31.1℃ and a negative temperature value, while the temperature of the part far from the frozen plate decreases slowly and with a small amplitude, which can be generally divided into the rapid cooling stage, slow cooling stage and overall stability stage. (2) Within 10cm of the frozen plate, most of the water in the soil samples exists in the form of ice crystals, and its volumetric water content decreases by 13.63%. In the range beyond 10cm of the frozen plate, with the increase of the distance between the TDR moisture collector and the frozen plate, the decrease of water content becomes smaller and smaller, and the volumetric water content at the furthest distance from the frozen plate decreases by 1.2%. (3) In the static state, after the saturated water replenishment process of 483h, the total water replenishment inside the soil tank is 22.9L; Under freezing conditions, after 423h freezing water replenishment process, the total water replenishment inside the soil tank is 30.23L. By studying the water migration of soil under freezing conditions, the water can enter into the soil and contact the soil to a greater extent, to make a basic analysis for the restoration of heavy metal contaminated soil by the freeze-thaw leaching method.

Keywords Artificial freezing, Contaminated clay soil, Temperature gradient, Water replenishment, Water migration

1. Introduction

As a direct or indirect "petri dish" for our food, fruits and vegetables, soil pollution also directly or indirectly affects our healthy life. According to the results of the National Soil Pollution Survey Bulletin released in November 2020: China's land pollution level is increasing, the overall situation of the soil is far behind compared with before, and the soil environment condition in some areas is even more serious, so it is urgent to repair polluted soil. Among many remediation methods, the most effective method is freeze-thaw combined with soil leaching technology, especially when the soil permeability coefficient is small and the clay content is large, which highlights its superiority. This technology has become one of the new methods for the rapid remediation of contaminated soil.

It is very important to study water migration under freezing conditions for the remediation of contaminated soil. Since the 1950s, international research on the mechanism of water migration and frost heaving in the process of soil freezing and thawing has begun[1]. The frost-heaving and thawing properties of soil mainly depend on the process of water migration, heat and mass migration and phase transformation in frozen soil[2].In recent years, there have been nearly 14 hypotheses on the driving forces of water migration in frozen soil: (1) capillary force;(2) internal static pressure of liquid;(3) crystallization power;(4) displacement of water in vapour state;(5) Pressure vacuole;(6) Suction tolerance;(7) osmotic pressure;(8) electroosmotic force;(9) vacuum suction force;(10) chemical potential;(11) The hydraulic pressure towards the freezing front decreases;(12) Hydraulic gradient in the frozen belt;(13) Spontaneous pore filling in the frozen zone;(14) Ice pressure gradient[3]. Under natural conditions, water migration in frozen soil depends on the synthesis of various physical and chemical factors, so each of the above hypotheses is only applicable to water migration under specific conditions[4]. According to classical physics, the energy of an object is composed of kinetic energy and potential energy. When water migration occurs due to soil freezing, the water flow speed is slow and the kinetic energy is negligible, leaving only potential energy. The potential energy possessed by soil water is called soil-water potential[5]. At the beginning of the 20th century, the Chinese Mechanical Soil Society proposed the division and definition of soil water potential energy, believing that the total potential energy of soil water is equal to the sum of the partial potential composed of pressure, gravity, temperature, substrate, solute and electricity, etc., among which any gradient of partial potential may cause water migration[6]. Many modern scholars believe that the research on water migration theory mainly includes theoretical models and water migration dynamics and that frost heaving is caused by the accumulation of a large amount of water during the freezing process, and the migration of water to the frozen area is completed under various gradients in the freezing process of soil[7].

Krieg[8] et al. proposed a method of reversibly building a closed low-temperature barrier to restrain pollutants, which can form a barrier surrounding the soil. Dash[9] demonstrated the effectiveness of artificial freezing barriers in controlling underground hazardous and radioactive wastes through laboratory experiments and field experiments. Gay[10],[11] et al. used the feature that water freezes into ice and impurities precipitate to remove heavy metal pollutants in soil. Ito and Takuto[12],[13]et al., according to the difference between the freezing point of pollutants and water, conducted extraction experiments in fine-grained soil by cryofreezing. Watanabe[14],[15] analyzed the formation of ice crystals and the migration of water and solutes near the ice crystals through unidirectional freezing experiments on glass powders saturated with different kinds of pollutants. Yang Sen[15] selected Cr^{3+} ions as pollutants to conduct one-dimensional freezing experiments, and concluded that too fast a freezing rate could not remove pollutants, and only when the freezing rate was less than a certain value would pollutants precipitate.

Based on the research on the basis of the lateral migration of water, freezing conditions in clayey soil pollution as the research object, first under the static state through automatic filling water device to test fully saturated soil, and record the static rehydration fluids, then open the frozen, refrigeration equipment under the condition of freezing, analysis of soil bin test the change of the internal temperature field and moisture field soil sample and the rehydration during the freezing,To explore the power consumption, the amount of liquid replenishment in standing, the amount of liquid replenishment in freezing period, and the change law of temperature field and water field in freezing process, so as to make a basic analysis for the restoration of heavy metal contaminated soil by freeze-thaw leaching method.

2 Test overview and test scheme

2.1 Test soil sample

2.1.1 Collection of test soil sample

The soil samples of this test were taken from the farmland near a smelting plant in Jiaozuo City, which belongs to polluted viscous soil. The physical parameters of the soil samples were determined according to the "Standard for Geotechnical Test Methods" (GB/T20123-2019). The basic physical indexes are shown in Table 1 below.

Table 1: Basic physical indexes of soil

Soil particle density (g/cm^{-3})	Maximum dry density ρ_d (g/cm^{-3})	Optimal water content ω (%)	Liquid limit ω_L (%)	Plastic limit ω_P (%)	particles (%)		
					≥0.25mm	0.075~0.25mm	≤0.075mm
2.67	1.70	19.0	29.9	16.0	24.20	22.08	53.63

2.1.2 Preparation and loading of test soil sample

The collected soil samples were repeatedly air-dried and ground, and the samples were screened with a sampling screen with a diameter of 5mm. The qualified soil samples were packed in sealed bags and placed in a storage room with moisture-proof isolation measures. At the same time, the water content of the screened soil was sampled and measured as the initial water content of the test soil sample preparation. Combined with the compaction curve and the optimal water content of the soil sample measured by the geotechnical test, the test soil sample was arranged according to the mass water content of 20%.

The volume of soil sample required for this test was calculated according to the test soil tank, combined with the geotechnical compaction test, and then the configured soil sample was loaded into the test soil tank. In this process, the compaction instrument is installed and placed smoothly, and the soil sample is placed into the instrument in layers. Each layer has the same thickness, and the compaction times of each layer are 25 times. After the compaction between the two adjacent layers is finished, the contact surface at the junction of the two layers shall be planed. After layering, the test soil is loaded until it is flush with the top surface of the frozen plate, as shown in Figure 1 below.

Figure 1

2.2 Freeze-thaw test equipment and Scheme

2.2.1 Test equipment

The model devices needed in the test mainly include the test soil tank, freezing and cooling system, automatic water refill device and data acquisition system, among which the data acquisition device includes a temperature acquisition instrument and water acquisition instrument. Among them, cuboid models with length, width and height of 170cm, 100cm and 100cm were selected for the test soil tank, and the material was welded by a steel plate with a thickness of 5mm. as shown in Figure 2 below.

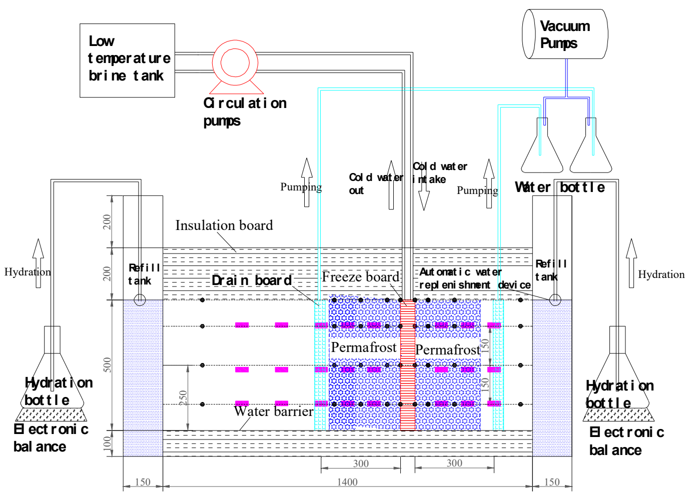
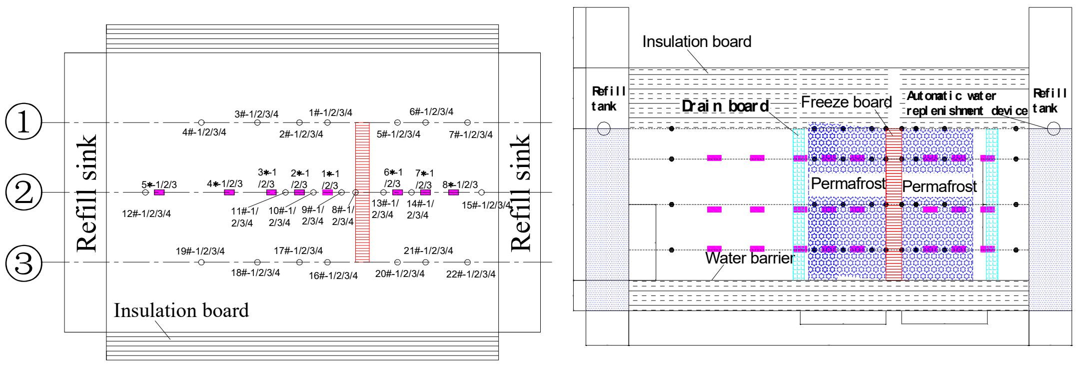


Figure 2

2.2.2 Sensor Layout

The soil is equipped with a temperature sensor and a moisture sensor[18], which are used to detect the temperature and moisture changes in the soil samples respectively. The layout plan and profile of the sensors are shown in Figure 3. The thermocouple sensors of the temperature acquisition instrument are arranged at a vertically downward position of 0cm, 10cm, 25cm and 40cm along the top surface of the freezing plate. In the horizontal direction, the thermocouple sensor of axis No. 2 is arranged at the left side of the freezing plate 5cm, 15cm, 25cm, 75cm, and the right side of the freezing plate 5cm, 15cm, 40cm; The thermocouple sensors of axis No. 1 and No. 3 are arranged at places 10cm, 20cm, 35cm, 55cm and 75cm on the left side of the freezing plate and 10cm, 20cm and 35cm on the right side of the freezing plate. The numbers are shown in Figure 3.

The red part in Figure 3 is the position distribution of the TDR moisture sensor, which is distributed 10cm, 25cm and 40cm below the top of the freezing plate. In the horizontal direction, the spacing of each of the three columns on the left and right sides of the frozen plate is 10cm, and the spacing of the last two columns on the left is 15cm.



(α) Σενσορ λαψουτ πλαν (β) Σενσορ λαψουτ προφιλε ·

Figure 3: Σενσορ λαψουτ

2.2.3 Test mechanism

Combined with the test equipment, according to the requirements of connection, and debugging, to ensure the accuracy of the experiment and the reliability of the data. Through the freezing refrigeration system, the test soil is cooled. Under the action of soil swelling and water absorption, the water in the filling tank migrates towards the freezing front, makes full contact with soil particles, absorbs more water, and forms an ice-like body. The test mechanism is shown in Figure 4 below.

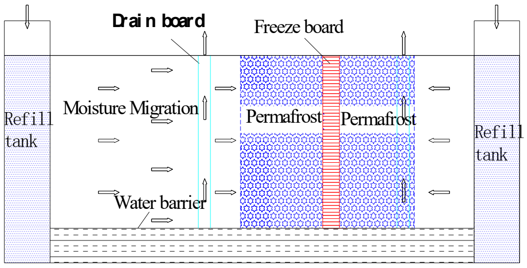


Figure 4

2.2.4 Test procedure

(1) The soil sample was air-dried, screened, bagged and sealed. The soil sample was configured according to the moisture content requirement of 20%, and the soil sample was filled with 1300kg in total. After the filling, the soil sample was left standing for 72 hours to ensure the uniform distribution of moisture.

(2) An automatic filling water device in the water storage tank filled with water, to the left and right sides of the fill in the sink to fill with water, and through the device makes the filling inside the tank liquid level height highly consistent with the test soil groove in soil samples, and fill the sink in the water is not falling, the test of the soil bin soil samples of soil water potential in balance, then by freezing refrigeration unit began to freeze.

(3) The temperature gradient mode of -2°C is adopted to freeze the soil samples through the freezing and refrigeration device until the soil samples in the test soil tank stop freezing when absorbing water during the freezing process.

(4) After a soil freeze in this test, 0-483h (about 20 days) is the static rehydration state, and 483-906h (423h in total, about 17 days) is the frozen rehydration state. Total 906h (total 37 days).

3. Test results and analysis

3.1 Freezing Mode

The cooling mode of the freezing plate is shown in Figure 5. During the freezing process (483h~906h), the initial temperature of the freezing refrigeration equipment is set at 4℃, and the cooling starts with a cooling gradient of -2℃, then drops to-20℃ and keeps the temperature unchanged. The freezing time is 17 days in total. Compared with the continuous freezing mode, the step-by-step freezing mode is more likely to cause soil frost to heave and absorb more water[19].In the state of standing water replenishment (0-483h), the surface temperature of the frozen plate gradually rises because the freezing refrigeration equipment is not started. During the freezing process, the surface temperature of the frozen plate continuously drops in a stepped manner. However, there is a certain difference between the surface temperature of the frozen plate and that of the saltwater tank, and the maximum temperature difference reaches 7.2℃. The reason is related to the energy exchange between the surface of the frozen plate and the surrounding soil and the energy loss during the refrigerant transfer process of the brine circulation system.

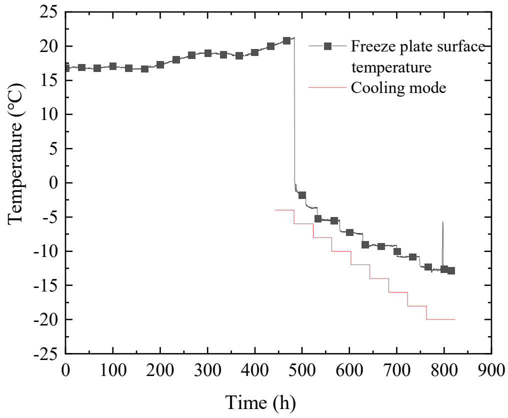


Figure 5: Συρφαχε τεμπερατυρε ανδ χοολινγ μοδε

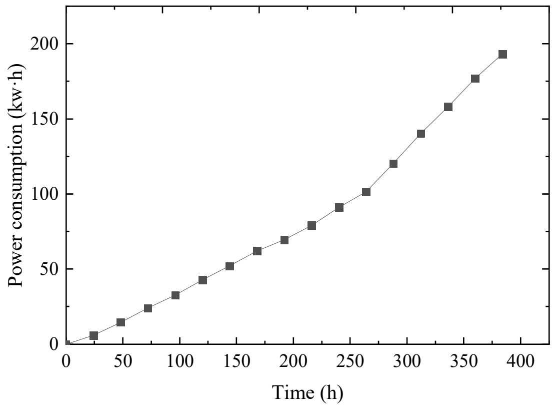


Figure 6: Σχηεματιχ διαγραμ οφ ποωερ χονσυμπτιον

During the 17-day freezing process, each device needs to work continuously, so the power consumption of this process is large. The seventeen days of meter readings were recorded and the electricity consumption diagram as shown in Figure 6 was drawn. As can be seen from Figure 6, power consumption is positively correlated with time. With the increase in freezing days, power consumption also increases. The total power consumption of this test is 193.25kw·h, indicating a suitable power consumption.

3.2 Temperature field analysis

The analysis of key point temperature in the soil is the most direct parameter to reflect the freezing effect. The change of temperature field in the soil sample can directly judge the freezing effect of this kind of freezing device. Figure 7 shows the temperature changes with time at the longitudinal depth of 25cm, The distance of the biaxial line from the freezing plate at different positions of the temperature versus time graph. It can be divided into three stages: rapid cooling stage, slow cooling stage and overall stability stage [19].

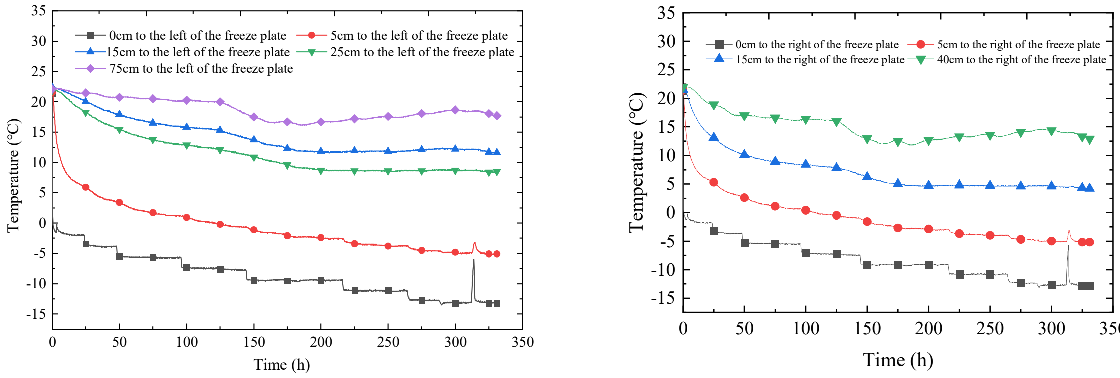
At the beginning of the cooling stage, the water near the freezing plate freezes in situ, and the soil temperature drops rapidly from the indoor temperature of 21.5℃. For the temperature within 5cm around the freezing plate, the temperature changes from positive to negative after about 1h. The temperature of soil 5cm on both sides of the frozen plate also drops to 5℃ about 40h after freezing.

The following 100h~250h is the slow cooling stage, Under the action of the freezing refrigeration device ② the temperature on both sides of the axis still keeps decreasing, However, the temperature of the soil at the distance of 75cm to the left of the freezing plate and 40cm to the right of the freezing plate is balanced.

During 250h~331h, the soil temperature within 5cm from the frozen plate still maintains a decreasing trend, but the decreasing rate decreases obviously. At the position 5cm away from the freezing plate, the cold energy provided by the freezing plate is offset with the temperature of the soil, and the soil temperature equilibrium has been reached.

In general, the temperature at 0cm on the left side of the freezing plate decreased from 22.1℃ to -13.2℃, a total decrease of 35.3℃. The temperature at 5cm drops from 22.1℃ to -5℃, a total decrease of 27.1℃. The temperature at 15cm drops from 22.1℃ to 11.6℃, a total decrease of 10.5℃. The temperature at 25cm drops from 22.1°C to 8.4°C, a total decrease of 13.7°C. The temperature at 75cm drops from 22.1°C to 17.7°C, a total drop of 4.4°C. The temperature at the right 0cm of the freezing plate decreased from 22°C to 12.8°C, a total decrease of 34.8°C. The temperature at 5cm drops from 22°C to -5.2°C, a total decrease of 27.2°C. The temperature at 15cm drops from 22°C to 4.3°C, a total drop of 17.7°C. The temperature at 40cm drops from 22°C to 13°C, a total drop of 9°C.

Negative temperature appeared within the range of about 5cm of the freezing plate, and the temperature decreased rapidly, with a temperature decrease of about 31.1℃. Soil samples outside the range of about 5cm of the freezing plate did not show negative temperature, and the range of temperature decrease gradually decreased with the increase of the distance from the freezing plate.

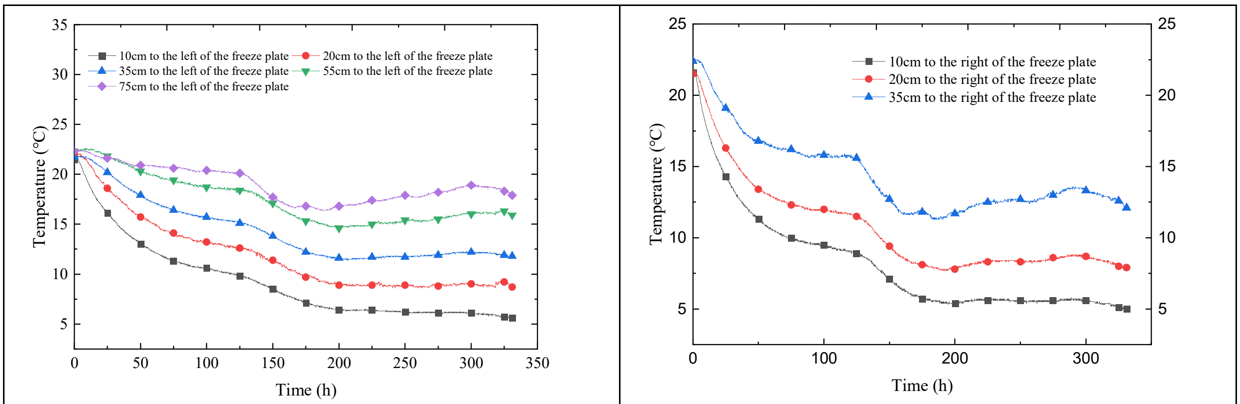


(a) Temperature of soil on the left side of the freezing plate *(b) Temperature of soil on the right side of the freezing plate*

Figure 7: Temperature changes at different positions of the two-axis from the frozen plate

Since ① axis and ③ axis are distributed symmetrically, the temperature variation curves of soil mass at different positions of ① axis from the frozen plate at the longitudinal depth of 25cm are made in the process of data processing, The soil temperature on the left and right sides of the frozen plate is shown in Figures 8(a) and 8(b) below.

The overall change trend of ① axis is similar to that of ② axis. At the beginning, the temperature drops rapidly, then gently, and finally reaches a stable state. However, because the position of the axis is relatively small, the cold energy provided by the frozen plate cannot completely offset the heat energy of the soil itself, resulting in the overall higher temperature of the ① axis than that of the ② axis.



(a) Temperature of soil on the left side of the freezing plate	*(b) Temperature of soil on the right side of the freezing plate*

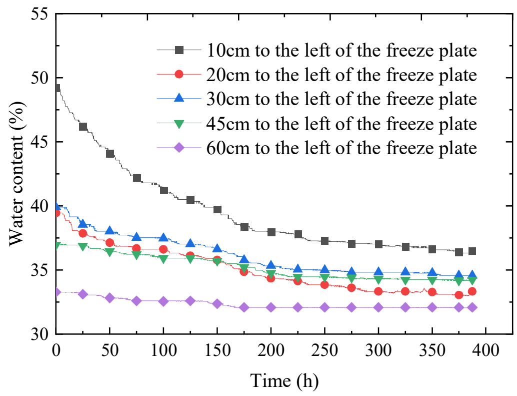
Figure 8: Temperature changes at different positions of the one-axis from the frozen plate

3.3 Analysis of water field

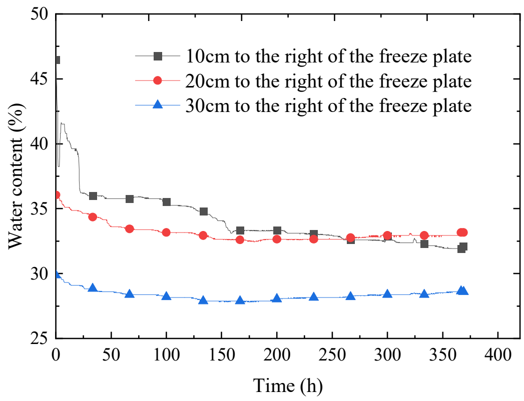
The distribution of the water field in the test soil tank can reflect the water migration in the soil sample. Before freezing, the water in the filling tank began to migrate to the soil sample under the action of its pressure and soil-water potential. When the water in the filling tank no longer decreased, the soil-water potential in the soil sample reached the equilibrium state. At this time, when the soil sample is frozen, the freezing plate starts to cool down under the action of the freezing refrigeration device, and the temperature of the soil on both sides of the freezing plate also starts to drop. The water in the unfrozen area begins to migrate to the freezing front under the action of "freezing suction", and the liquid in the filling tank is absorbed by the soil accordingly. The volumetric moisture content at each monitoring point can be measured by a TDR moisture sensor embedded in the soil. As shown in Figure 9 below, at the longitudinal depth of 25cm, the change curve of the volume water content of each monitoring point on the central axis over time.

As can be seen from Figure 9, the rate of water content decline at 10cm to the right of the freezing plate is different from that at the left of the freezing plate. The volume of water content at 10cm to the right of the freezing plate drops sharply. This is because, during the initial cooling process, the soil 10cm to the right of the freezing plate drops to a negative temperature and the surrounding water freezes in situ. Resulting in a rapid decline in volume water content. In general, the volume of water content on both sides of the freezing plate presents a downward trend, but with the increase of the distance from the freezing plate, the decline of volume water content gradually decreases. The specific data is as follows: The volume of water content at the distance of 10cm, 20cm, 30cm, 45cm, and 60cm from the left side of the frozen plate decreased from 49.22% to 36.51%, 39.46% to 33.33%, 39.91% to 34.58%, and 36.96%, respectively34.25% and 33.22% decreased to 32.09%, down 12.71%, 6.31%, 5.33%, 2.71% and 1.13%, respectively. The volume water content of 10cm, 20cm and 30cm away from the right side of the frozen slab decreased from 46.46% to 31.92%, 35.9% to 33.11% and 29.89% to 28.65%. Decreased by 14.54%, 3.89% and 1.24%, respectively.

As the freezing front moves towards the filling tank, the water in the soil 10cm and 20cm away from the freezing plate becomes ice, and the content of liquid water decreases. Therefore, the water content in the soil sample shows a decreasing trend, while the temperature of the soil sample 30cm, 45cm and 60cm away from the freezing plate has not decreased to negative temperature. There is no significant change in liquid water in the soil, so there is no significant change in water content.



(a) Moisture content change on the left side of the freezing plate



(b) Moisture content change on the right side of the freezing plate

Figure 9: Changes in moisture content at different positions of the central axis from the frozen plate

3.4 Analysis of liquid replenishment volume

3.4.1 Standing fluid rehydration

After the soil sample is filled, all devices are connected and the automatic water refill device starts to work. The replenishment liquid in the filling tank is at the same level as the soil sample in the test soil tank. Under the action of gravity potential, the liquid in the tank begins to infiltrate into the soil sample until the liquid level in the tank no longer drops. This indicates that the soil-water potential in the soil sample is balanced, which can ensure that the amount of liquid replenishment during the freezing period can exclude the influence of the gravity of the liquid in the replenishment tank. The liquid replenishment amount of soil in a static state is shown in Figure 10 below. The initial (0~25h) is the rapid infiltration stage, the subsequent (25~400h) is the slow infiltration stage, and the last (400h~483h) is the stable state. The final replenishment amount on the left side of the freezing plate is 15.21L, the final replenishment amount on the right side of the freezing plate is 7.69L, and the total replenishment water inside the soil tank is 22.9L.

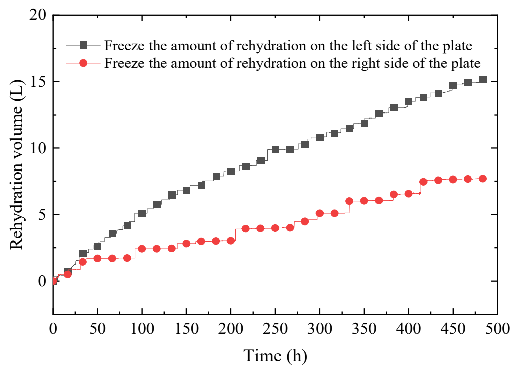


Figure 10: Fluid replenishment during the standing period

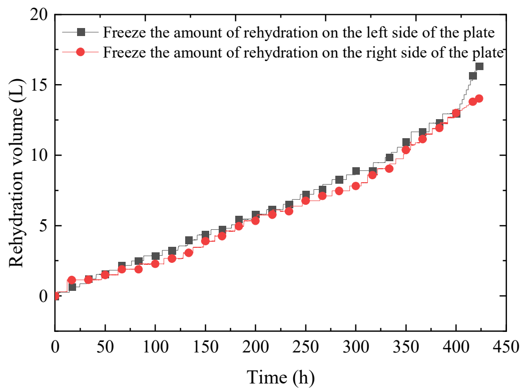


Figure 11: Fluid replenishment during freezing period

3.4.2 Replenishment amount during freezing period

When the soil-water potential in the test soil tank reaches equilibrium, stepwise freezing is carried out through the freezing refrigeration device. It can be seen from Figure 11 that the amount of water rehydration is positively correlated with the freezing time. In the soil pore water reach the freezing temperature, ice crystals are generated in soil moisture between soil water potential function affecting grain drawn into ice crystals, which makes the soil near the ice crystal particles between the water film thickness thinning, until this area of moisture is absorbed completely, in the freeze front water completely frozen, and then in turn cycle this process, The freezing front continues to migrate, so that the water migrates, in turn, to promote the continuous replenishment during the freezing period. The process is then repeated so that the stepped-up trend in the figure appears. During the freezing process, the replenishment amount on the left side of the freezing plate is 16.331L and that on the right side is 13.897L. After 423h, the total replenishment amount in the soil tank is 30.228L.

4. Conclusion

This article rely on frozen soil frost heave and properties of clayey soil as the research object, by using the method of artificial freezing, study filling liquid in the tank under the action of "frozen suction to the effects of migration in soil samples, and analyzes the amount of power consumption, let stand rehydration and freeze in the process of rehydration and freezing temperature field and moisture field in the process of change, The basic analysis was made for the remediation of contaminated soil by freeze-thaw leaching. The following conclusions are reached.

(1) The temperature analysis of the monitoring points inside the soil tank is as follows: the temperature of parts within 5cm from the freezing plate decreases rapidly and with a large range, with a temperature decrease of 31.1 ℃ and a negative temperature, while the temperature at a distance from the freezing plate decreases slowly and with a small range. As the distance from the freezing plate increases, the temperature decrease is not obvious. The whole can be divided into the rapid cooling stage, slow cooling stage and overall stability stage.

(2) The TDR water collection instrument on the two axes can detect that within 10cm of the freezing plate, the water in the soil sample is mostly in the form of ice, and Its volumetric moisture content is reduced by 13.63%, In the range beyond 10cm of the freezing plate, as the distance of TDR moisture collector from the freezing plate increased, the decrease of water content became smaller and smaller, and the volume water content at the farthest distance from the freezing plate decreased by 1.2%.

(3) Under the use of an automatic water refill device, the inside of the filling tank should keep the sufficient liquid. In the static state, after the saturated replenishment process of 483h, the water replenishment inside the soil tank is 22.9L. Under freezing conditions, after the 423h freezing water replenishment process, the total water replenishment inside the soil tank is 30.23L. After the soil is frozen, the amount of rehydration in the soil tank increases obviously.

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