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Experimental research on evolving rules of segregation ice in artificial frozen soil

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Abstract

The foundation of frost heave controlling is the research on evolving rules of segregation ice. The evolving rules of segregation ice have been researched systematically by one-dimension freezing experiments. The technique of dynamic photograph has been applied in research for the first time. The research on segregation ice indicated that three phases can be divided according to the change of temperature field: few segregation ices appeared in the first phases, several thin and discontinuous segregation ices appeared in the second phases, segregation ice evolvement was mainly the growth of final ice lens in the third phase when the freezing front tended to be stable.

Keywords: artificial frozen soil; segregation ice; evolving rule; image analysis

1. Introduction

The technology of artificial frozen soil used for the reinforcement of moisture, instability strata has characteristics of strong adaptability, high reliability, non-polluting, simple equipment and better tech-economic effect [1]. However, ice segregating which caused by the moisture migration during artificial ground freezing will bring large frost-heaving deformation and frost-heaving force.

The research on frost heave focused on the factors of frost heave, heat and moisture transfer rules during soil freezing, frost heave rules, frost heave model, as well as the frost heave forecast in China and other countries. The first frost-heaving theory (Capillary theory) [2] and the second frost-heaving theory (frozen fringe theory) [3] have been put forward. The second frost-heaving theory is a major development. It has become a hot spot in the field of frozen soil. With the development of the frost-heaving theory, the model for frost heave forecast and simulation has been improved greatly from empirical formula to heat and moisture coupled model [4], rigid ice model [5], segregation potential model [6], and thermodynamic model [7] and so on.

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With the progress of the test apparatus and analysis, the experiment study on frost heave has been gradually developed. XU Xue-zu [8] tested moisture migration and ice segregation structure and obtained the basic characteristics of ice segregation structure. Li Ping [9] analyzed the characteristics of frozen fringe in saturated soil during freezing by using the digital technique of picture (duplicated film), carried out the transformation between the static test results and the dynamic analysis of ice segregation process. Konrad [10] studied the frost heave characteristics of stepwise freezing and jumping freezing model according to the ice lens mechanism. Zhou Guo-qing [11-12] analyzed the differences and its cause in soil temperature, temperature gradient and frost-heave amount by numerical simulation on intermittent and continuous freezing model. BIE Xiao-yong [13] studied the temperature field and the frost-heave amount of silty clay under the modes of continuous freezing, intermittent freezing and stepwise freezing, and concluded that the frost heave was controlled by the change of freezing mode. Shang Xiang-yu [14] studied the optimal freezing model of frost heave control. Zhou Jin-Sheng [15] investigated the evolving rules of frost heave and the relationship between frost heave control and freezing mode (i.e. the continuous freezing, the intermittent freezing of time control mode and depth control mode).

Although the mechanism, simulation and forecasting of frost heave have always been the cores and hotspots in academic research on frozen soil [16], few systematic investigations were done on the evolving rules of segregation ice, and unified theory system was not formed [17]. In order to control the frost heave, experimental research on evolving rules of segregation ice in artificial frozen soil under different freezing temperatures was done in this paper to obtain the formation mechanism & evolving rules of frost heave in artificial frozen soil.

2. Experiment scheme

2.1. Experiment System

The experimental system consists of temperature control system, test system, water supplement and freezing sample tube.

(1) Temperature control system is a cold bath.

(2) Test system includes four parts: 1) temperature field testing: the thermal resistance whose accuracy is ± 0.1% was set along vertical direction at 1 cm interval to collect the temperature changes in the course of the experiment synchronously; 2) Frost heave testing: the testing range and accuracy of displacement sensors are 50 mm and 0.01 mm respectively; 3) Dynamic microcosmic real-time monitoring: a video microscope with 50 to 7,000 times digital zoom was used to obtain digital image. The pixel was set as 640 × 480. The time interval was 10 minutes; 4) Data recording: test data were recorded with the data acquisition instrument DATATAKER.

(3) In order to obtain the visual information of the test process, a square organic glass tube was used. Its internal dimensions are 11cm × 11cm × 15 cm. The transmittance of organic glass is 95%.

2.2. Parameters of soil samples

Test sample was the silty clay with frost heaving susceptibility. The analysis results of soil grain are shown in table 1. Remolded soil samples with 27% moisture content were made after dried, crushed and watered.

Table 1. Analysis results of soil grain

	Fine Sand	Micro-Sand	Coarser Silt		Fine Silt	Clay	
Grain Size	0.25~0.075	0.075~0.05	0.05~0.02	0.02~0.01	0.01~0.005	0.005~0.002	0.002~0.001
Percent	1.6	3.9	23.5	21	17	18	15

2.3. Temperature control

Three continuous freezing tests with different temperature gradients were carried out to analyze the influence of temperature gradient on evolving rules of segregation ice under continuous freezing. The temperature control schemes are shown in table 2. All the tests were in open system, and test soil samples had been precooled.

Table 2. Temperature control schemes of continuous freezing experiment

No.	Cold end temperature	Warm end temperature	Environmental temperature
A1	-18 ℃	+12 ℃	+2 ℃
A2	-22 ℃	+12 ℃	+2 ℃
A3	-26 ℃	+12 ℃	+2 ℃

3. Analysis of experimental results

3.1. Image Processing

For more detailed and accurate evolution of segregation ice, the gray-scale image processing has been done. Segregation ice photo and binarization image of ice & soil are shown in Fig. 1 (a) and Fig. 1 (b). The white pixel block stands for segregation ice and the black pixel block stands for soil in Fig.1b. Test results, such as the thickness of frozen and unfrozen soil, the thickness, distribution and growth rate of segregation ice could be determined by counting pixel blocks.

Fig. 1. (a) Segregation ice photo; (b) Binarization image of frozen soil

3.2. Analysis of segregation ice growth phase

According to image analysis, the evolution of segregation ice showed the characteristics of phases in continuous freezing experiment. Based on the typical time of the freezing process, the developing process of the segregation ice can be divided into three main phases:

(1) Phase 1: the early freezing, as a result of rapid development of the freezing front position, there were hardly any segregation ice.

(2) Phase 2: with the freezing speed decreased gradually, a spot of thin discrete segregation ice layer generated. the average thickness of the thin segregation ice layer is defined as D_1.

(3) Phase 3: when the freezing front position stabilized gradually, the segregation ice rounded into an ice layer through the freezing surface, which was named final ice lens. The frost heave was caused by the final ice lens growth in this phase. The thickness of the final ice lens is defined as D_2. The phases of these three continuous freezing tests from image analysis are shown in table 3.

Table 3. Three phases time from image analysis

No.	Phase 1 (min)	Phase 2 (min)	Phase 3 (min)
A1	0～740	740～1080	1080～4560
A2	0～660	660～960	960～4990
A3	0～630	630～870	870～4960

Fig. 2 shows the relations between freezing front position and test duration tested by the thermal resistor in continuous freezing test samples. The three phases of freezing front position shown in Fig. 2 are relevant to the three phases that obtained from image analysis (Table 3).

3.3. Analysis of segregation ice thickness

The curve of total segregation ice thickness versus test duration in Fig. 3 was obtained from the image analysis of continuous freezing test (A1). The curves of final ice lens thickness versus test duration are depicted in Fig.3 which is a part of the curve of frost heave versus test duration in the third phase tested by displacement transducer.

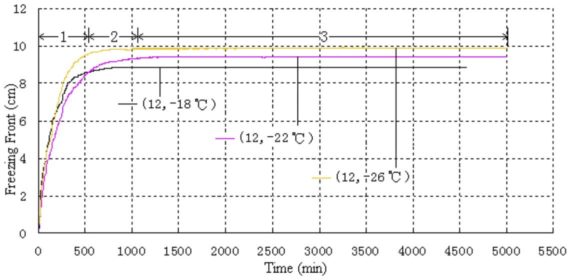

Fig. 2. Freezing front position of three group continuous freezing experiment

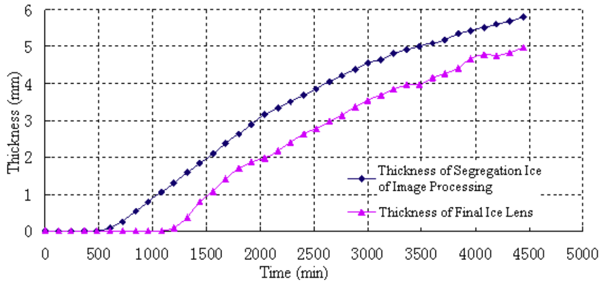

Fig. 3. Thickness of whole segregation ice and final ice lens in continuous freezing experiment (A1)

Fig. 3 shows the curve of total segregation ice thickness versus test duration is consistent with the curve of final ice lens thickness versus test duration in continuous freezing test (A1). The two curves are approximately parallel in phase 3 (after 1080min). The total thickness of segregation ice is 0.953 mm which is thicker than the final ice lens thickness. It is caused by 4 to 5 thin discrete segregation ice layer evolved in phase 2 of continuous freezing (740 ~1080min). So it can be proved that there is only the growth of final ice lens in the third phase, and it is feasible to represent the total thickness of segregation ice with the thickness of the final ice lens and the thickness of thin discrete segregation ice layer evolved in phase 2. The frost heave in phase 3 is equal to the thickness of the final ice lens.

3.4. Analysis of evolving rules of segregation ice

Based on the analysis of the phases in the freezing process, we know that the total thickness of segregation ice D is the sum of the segregation ice thickness evolved in the second and third phases of one-dimensional freezing soil. That is:

$$D = D_1 + D_2 \tag{1}$$

Where, D_1 is the thickness of thin discrete segregation ice layer evolved in phase 2, mm; D_2 is the thickness of the final ice lens evolved in phase 3, mm.

(1) Evolving Rules of Segregation Ice in Phase 2

In the course of the experiment, the thin discrete segregation ice layer evolved in phase 2 was mainly due to the redistributing of water in soil. The thicknesses of thin discrete segregation ice layer evolved in phase 2 were 0.953 mm, 0.688 mm, 0.447 mm respectively, and the corresponding durations in phase 2 were 340 min, 300 min and 240 min respectively in three continuous freezing tests (A1 ~ A3) with different temperature gradients. Fig. 4 shows the relation of duration and segregation ice thickness in phase 2. Fig. 5 shows the relation of duration and temperature gradient in phase 2.

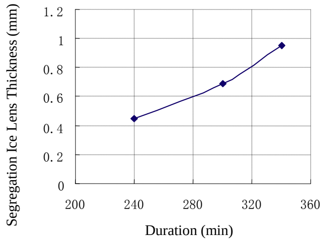

Fig. 4. Relation of duration and segregation ice thickness in second phase

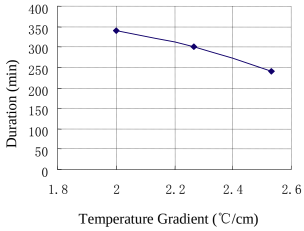

Fig. 5. Relation of duration and temperature gradient in second phase

It can be seen from Fig. 4 and Fig. 5 that there is approximately linear relationship between the duration and segregation ice thickness in phase 2 as well as between the duration and temperature gradient. Therefore, there exists linear relationship between segregation ice thickness and temperature gradient in phase 2. We can find the relation of segregation ice thickness and temperature gradient by linear fitting:

$$D_1 = -0.9488 \times \mathrm{grad}_0 T + 2.8466 \tag{2}$$

Where, $grad_0T$ is the temperature gradient of one-dimensional freezing test, ℃/cm. The correlation coefficient is 0.9993. The scope of application is 2～2.53℃/cm.

(2) Evolving Rules of Segregation Ice in Phase 3

As a result of the smaller proportion of the segregation ice in phase 2 to the total segregation ice, the research on evolving rules of segregation ice focused on the evolving rules of the final ice lens. Three curves of final ice lens thickness versus test duration in continuous freezing tests with different temperature gradients are shown in Fig. 6. The setting value of time in Fig. 6 is the duration of final ice lens growth, i.e. the time in phase 3 of freezing tests.

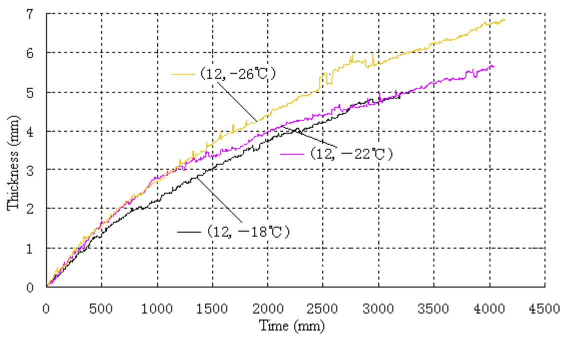

Fig. 6. Relation of duration and thickness of final ice lens in three group continuous freezing experiment

Fitting parameters and correlation coefficients could be obtained by fitting the three curves with a quadratic function

$$D_2 = p_1 \times t^2 + p_2 \times t \tag{3}$$

Where D_2 is the thickness of the final ice lens, mm; t is the freezing time, min.

Table 4. Fitting parameters and related coefficients

No.	P_1	P_2	Correlation coefficient
A1	-2.512*10^(-7)	0.002313	0.9974
A2	-3.175*10^(-7)	0.002584	0.9889
A3	-3.125*10^(-7)	0.002884	0.995

4. Conclusions

(1) The quantitative analysis on the evolution rules of segregation ice can be brought into effect by introducing the real-time shooting and the image processing. Based on these technologies, we can well and truly obtain the parameters such as the thickness of unfrozen and frozen soil, the thickness, the position and the growing rate of segregation ice.

(2) According to the typical time of the freezing tests, the developing process of the segregation ice in continuous freezing experiment can be divided into three main phases: the early freezing, the thin discrete segregation ice layer growth and the final ice lens growth.

(3) The quantity of the thin discrete segregation ice is few in one-dimensional open system freezing tests. So, the segregated heave is mainly caused by the growth of segregation ice in phase 3, i.e. the growth of the final ice lens.

(4) The evolution rules of segregation ice in continuous freezing tests with different temperature gradients have been obtained by mathematical analysis. There is linear relationship between segregation ice thickness and temperature gradient in phase 2. The thickness of segregation ice is a function of time in phase 3.

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