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Experimental Study on Thawing Process of Frozen Soil Based on CT Scanning

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ABSTRACT: In order to explore the feature of frozen soil thawing based on CT scanning, the experiment is carried out under the indoor temperature of 20℃. The sample of frozen soil which is -27℃ is taken into isothermal air to melt by natural convection. And the CT images are obtained by X-ray scan, and at the same time, its temperature-time history is recorded. The curve of grayscale-time is acquired by counted CT images at each moment, and compared with its temperature time history. The results show that the average grayscale increases obviously with temperature rising and thawing in frozen soil. However after sample thaws completely, the average grayscale is not practically changing even temperature still rising. A break point is obviously observed in the graph of grayscale-time at the moment of phase-transition finished, which is considered as a symbol of the completion of frozen soil melting.

KEYWORDS: Frozen soil; X-CT; Average grayscale; Thawing.

INTRODUCTION

CT technology (Computerized Tomography) refers to a digital image of the μ value distribution of an object's fault. Through the X-ray penetrating objects section, the decaying information of different material after X-ray running through this layer is collected and calculated by computer to obtain the quantitative data that reflect the absorbing coefficient (μ value) of the substance on the fault [1]. In the study of image of frozen soils using CT technology, Pu Yibin compare the CT images of ice, water, air and soil particle in frozen soil. And he finds significant difference in the data through observation of the images and points out that the mixtures of phase states are reflected in intermediate data [2]. By mathematical analysis and experimental regression, the mathematical equation of CT in frozen soil is deduced, and the accurate relationship between the data of CT image and the parameters of frozen soil is established [3]. Wu Ziwang and other scholars analyze the change of structure and volume of frozen soil by using CT image. They believe that the change of CT value during the frozen soil creep is mainly controlled by the change of material density of each point in frozen soil [4]. On the basis of these achievements, domestic scholars start to study meso-structural properties of frozen soil or frozen rock, mainly using CT equipment to scan and record the variation characteristics of microstructure in the uniaxis compression of frozen soil under different loading stages, damage propagation characteristics of rock under freezing and thawing conditions, meso-structural change and water migration of rock mass [5]. The main characteristics of these studies are taking the influence of the negative temperature factor on the characteristics of frozen soil into consideration.

PREPARATION OF SOIL SAMPLE

The test sample used in this experiment is the original silty clay (brown yellow) of Tianjin. The basic physical properties of the soil is as following: thermal conductivity λ=1.61W / ($m \bullet K$) , thermal diffusivity $\alpha = 0.00222 m^2 / h$, specific heat capacity $C = 1.35 kJ / (kg \bullet K)$, moisture content $w = 24.02\%$, bulk density γ=20.3kN / m^3 , soil particle proportion $G_s = 2.7$, natural void ratio $e = 0.646$, liquid limit $W_L = 26.7\%$, plastic limit $W_P = 18.6\%$.

In the refrigerator of -27℃, place a silty clay sample with the mass of m=68.204g, diameter of 30.2mm, and height of 47mm. Make it quickly frozen, and stay stable for 24 hours.

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According to Lumped Parameter Method in Heat Transfer Theory, when the resistance of heat exchange on the surface of the object is much larger than the internal thermal conduction resistance, the temperature within the object field tends to be consistent. It can be considered as that the whole object is under the same temperature at the same time. The temperature field inside the object is only related to the time, and has nothing to do with its geometric property and the space position. Therefore, the temperature of any point can be used to replace the temperature of the object, namely the quality and heat capacity of the object is considered as being concentrated at this point.

The application of Lumped Parameter Method is limited which requires that the thermal resistance inside the object can be neglected, that is, at any moment, the temperature within the object is the same. However in the practical application, it is generally required that the maximum deviation of the temperatures of all points of the object is not more than 5%. Usually it is judged by B_i and the judgment method is shown in Formula (1).

$$B_i = \frac{hl_c}{\lambda} \leq 0.1 \tag{1}$$

In Formula (1), $l_c = V / A$ represents the feature size, V represents the sample size, A represents the surface area of the sample; h represents the surface heat transfer coefficient, $W / (m^2 \bullet K)$ λ represents the thermal conductivity of the solid.

Based on past experience, h the surface heat transfer coefficient of soil and air is generally $12 \sim 15W / (m^2 \bullet K)$. For the silty clay used in this experiment, the thermal conductivity under normal temperature is generally λ=1.61W/(m $\bullet$ K) .

As the characteristic length of the small sample is $l_c = V / A = 5.7142mm$, the value of B_i is:

$$B_i = \frac{hl_c}{\lambda} = 12 \times 5.71 \times 10^{-3} / 1.61 = 0.043 < 0.1$$

The results indicate that the heat resistance of the soil surface is much greater than the internal thermal resistance, which means that the external heat will be quickly and evenly distributed on the whole sample. When the temperature is negative, the water in the soil will be frozen into ice. As the thermal conductivity of water is much lower than that of the ice [6], the external heat can be more quickly distributed throughout the sample evenly.

EXPERIMENT PROCESS

First, frozen the silty clay sample to -27 C, and place it under indoor temperature of 20 ℃. Use isothermal air to melt the sample by natural convection. Carry out CT scanning operation at the same time, as shown in Figure 1. Place the heat sensitive resistor in the center of the soil sample, and the change of the center temperature with time is recorded by the intelligent universal meter. The result is shown in Figure 2. Scanning the gray Grayscale images of the soil samples at each moment obtained by CT scanning are shown in Figure 3.

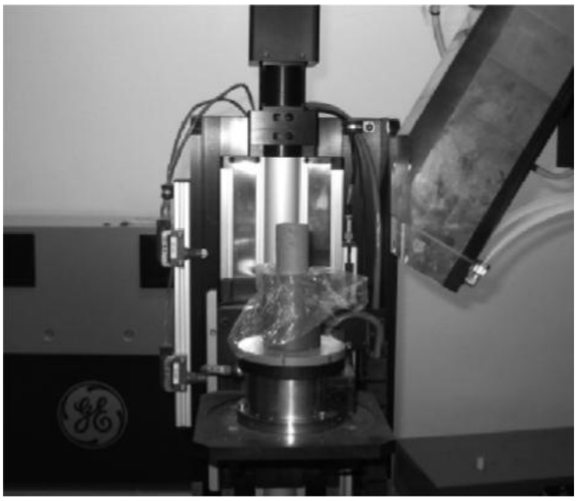

Figure 1. Scanning in the Experiment.

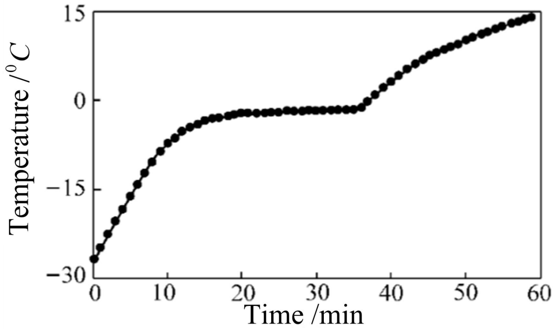

Figure 2. Measured Value of Sample Temperature with Time Changing.

According to Figure 2, it can be seen that the temperature of the soil basically has experienced 3 stages:

(1) In the 0~10min, temperature of the frozen soil increase rapidly from 27 ℃ to -7℃. According to the previous studies, at this stage, content of unfrozen water in the frozen soil generally does not change and the main external performance is the rapid increase of temperature of the frozen soil sample.

(2) In 15-38 min, the temperature of the frozen soil is stabled in range -2.5-1.5 ℃. At this stage, the soil samples absorb a lot of heat from the outside world, but temperature change is very small, which indicates that this process is mainly the phase change process where the ice in the soil absorbs heats and melts into water.

(3) After 38min, the phase change of the frozen soil is finished. Heat absorbed from the outside is used to increase the temperature of the soil, which is mainly reflected by the rapid increase of the temperature of the soil sample.

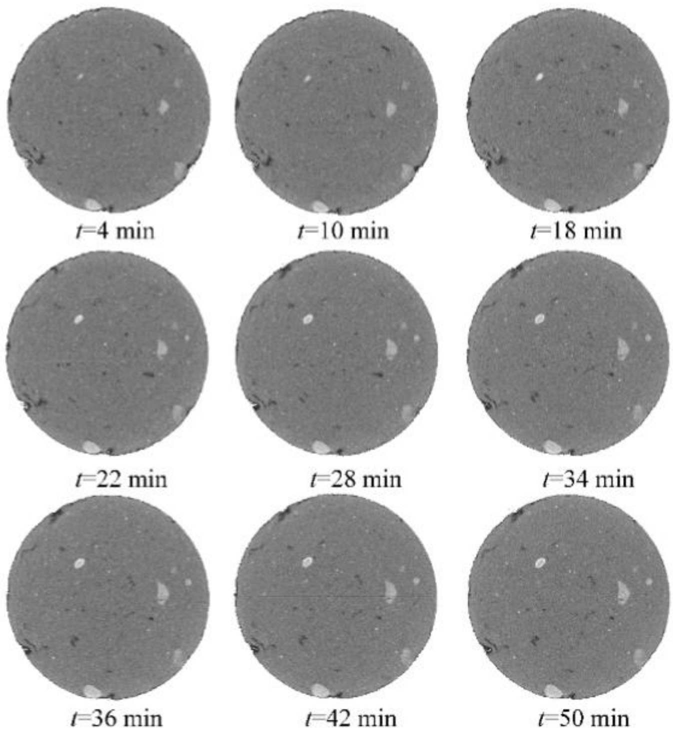

Figure 3. CT Images during Frozen Soil Melting.

In this experiment, the CT gray scale image from the initial frozen soil to the melting soil is obtained by CT scanning, namely the Figure 3. And the following conclusions can be acquired by analysis:

(1) Due to the uniformity of soil samples and its small enough volume, the grayscale of CT image remains uniform throughout the experiment which means that temperature field of whole sample is basically uniform during the whole process of the experiment.

(2) At the initial stage, the grayscale of CT images distribute evenly. The ice crystal in the frozen soil is the whole structure, and the grain and ice can not be clearly distinguished.

ANALYSIS OF EXPERIMENTAL RESULTS

CT images obtained in this experiment are processed by the following methods: as shown in Figure 4, take rings of a certain width from the center of the circle along the radial (the test selects R/10, R is the radius of the soil sample, as a statistical ring width). According to the normal distribution statistical method, calculate the mean and variance of the gray values of the pixels on the ring. The mean reflects the mean values of grayscales within selected ring [7], and the variance reflects the discrete degree of the grayscale value within selected ring.

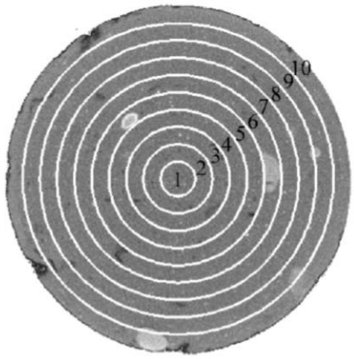

Figure 4. Division of Statistical Region of Grayscale Images of Frozen Soil.

According to the method shown in Figure 4, make statistic of distribution of the mean values of radial grayscale in the radial direction of the CT image at each moment and the statistic result is shown in Figure 5 (a) and 5 (b).

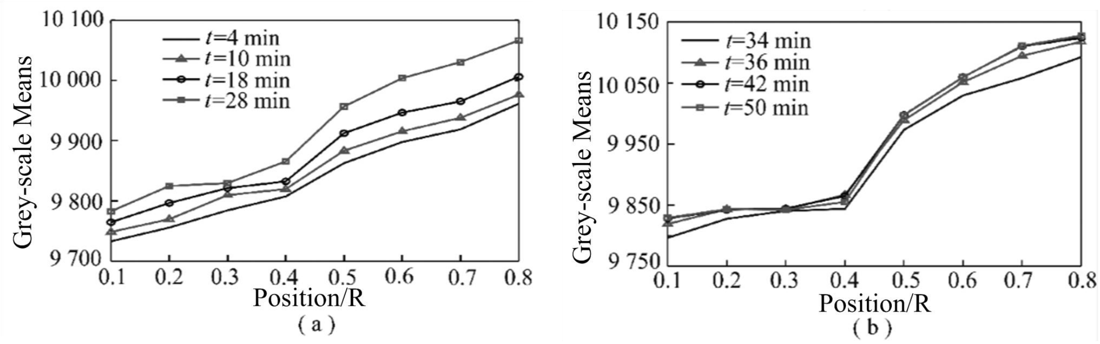

Figure 5. Grey-scale Means of Each Ring of Frozen Soil.

Make statistics of changes of CT image grayscale mean values on each ring over time, and the results as shown in Figure 6. Grayscale means of four rings (0.4R~0.5R, 0.5R~0.6R, 0.6R~0.7R, 0.7R~0.8R) are selected to observe their variation curve with the time changing respectively.

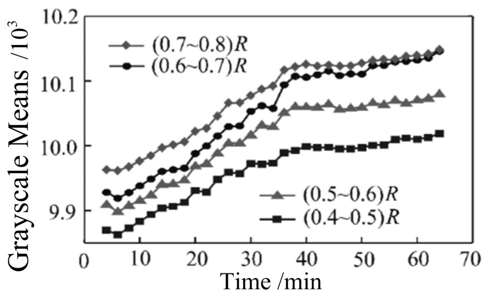

Figure 6. Changes of Grayscale Means of Each Ring with Time.

As shown in Figure 5, make statistic of the ring grayscale means of CT grayscale images of the soil sample. Taking the damage of the edge of the sample into account, this experiment selects 8 rings within 0.8R for statistical analysis. Make statistics according to the normal distribution [8]. Figure 5 (a) is the change process of grayscale value during temperature the frozen soil rise rapidly until its melting stage. Figure 5 (b) is the stage from frozen soil experiences violent phase transition to the phase transformation gradually stop. Through analysis and comparison, the following conclusions can be drawn out:

As shown in Figure 5 (a), because of the existence of cup-shape artifact in a CT scan, in the spatial distribution, the initial state of the ring gray value is mainly manifested as the center of the gray value is lower than the external gray value. For example, in the fourth minute after the beginning of the experiment, in the spatial distribution, grayscale value of soil sample is mainly manifested as the unevenness with higher on the edge and lower in the middle. Until the 42nd minute to the 50th minute (Figure 5 (b)), the final grayscale value of soil sample tends to be stable and in the spatial distribution, grayscale value of soil sample still shows an unevenness with higher on edge and lower in the middle.

Grayscale values change with time: according to the above analysis of Figure 2, during the process of frozen soil thawing and temperature rising (namely in the 0~38min) with time changing, the grayscale mean value within the annular area shows gradual upward trend as shown in Figure 6. In the process of temperature rising, with the change of time, the grayscale value of frozen soil is increasing, and the time when temperature of soil sample rises from -27℃ to -7℃ is 0~10min. During this process, the temperature of the soil sample is lower than -7℃ and basically does not have the phase change [9]. But in Figure 5 (a) and Figure 6, the average gray value of each ring is still kept rising. Therefore, in the process of temperature rising, even if there is no obvious phase change in the frozen soil, the grayscale mean will still have a significant rise.

As shown in Figure 6, after the frozen soil thaws (after about 38min), with the time changing, the variation of the grayscale means within the ring area significantly reduces without significant change. According to Figure 5 (b), there is no significant change in the grayscale value during 36~ 50min and the images are coincident with each other. However, according to Figure 2, at this stage, temperature of the soil sample rises quickly from 0℃to 10℃stage after melting with significant change in temperature. Therefore, it can be concluded that as for melting soil after the end of the phase change process, even if the temperature rise largely, the grayscale image does not change much.

About at 38min, with the time changing, the variation of the grayscale mean within ring changes sharply which is shown as a clear break point in the image as shown in Figure 6. Compared with Figure 2, the phase transition is completed around 38min, and the temperature begins to show a clear upward trend. Therefore, this point can be regarded as a sign of the finish of frozen soil melting.

Aiming at the conclusion, this paper presents a mathematical model fitting the grayscale means G of each statistical ring which change with time, as shown in Figure 7.

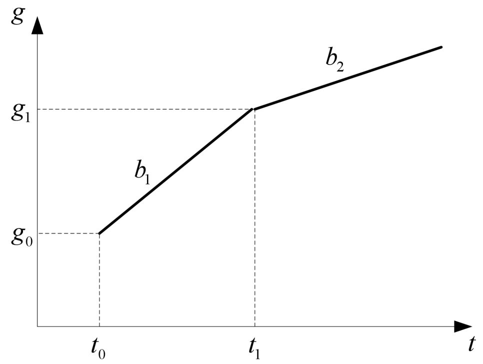

Figure 7. Variation Model of Grayscale Mean in Ring

The mathematical formula corresponding to the mathematical model is as follows:

$$g = \begin{cases} b_1 t + (g_1 - b_1 t_1) & (0 \le t \le t_1) \\ b_2 t + (g_1 - b_2 t_1) & (t \ge t_1) \end{cases} \tag{2}$$

In the Formula (2), t represents the time; g represents the grayscale level; and the slopes of the two broken lines are expressed by b_1 and b_2 respectively.

The data in Figure 6 is fitted by the Formula (2), and the obtained results are shown in Figure 8.

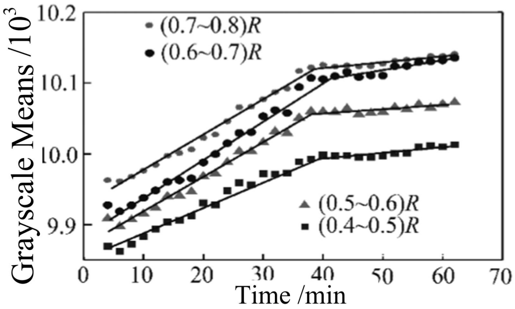

Figure 8. Fitting Results of Grayscale Means in Rings

The time of the break of the grayscale means of each ring (from the inside to the outside) is calculated as 37.3, 38.1, 40.1, 38.6min. According to the variation of grayscale means in each ring whit time changing, which is reflected in Figure 8, the following conclusions can be drawn out:

(1) Observe the changes of grayscale means of the images after the appearance of the break point. With the time changing, grayscale means show a slight upward trend. Therefore it can be presumed that, with temperature rising continuously, grayscale value of thawing soil CT scanning image will rise slightly and the rising volume is small.

(2) Observe the time when the break point of the grayscale value of each ring appearing. It can be considered that the soil sample is melted in a relatively close time range. This phenomenon reflects the volume of soil sample used in the experiment is small enough and the change process of its internal temperature field is generally uniform.

(3)Analyze the final stable state of grayscale means of each ring. In soil sample, the grayscale value of the inner part is lower than that in the outer part. According to the different positions of the ring, the final grayscale value stays around different numerical ranges. This phenomenon once again shows that for the average soil in the mean soil temperature, the CT scanning image is not uniform.

(4) Observe the change of image grayscale means before the appearance of break point. The grayscale means have been increasing obviously, which indicates that the ice melting in the soil can cause the increase of grayscale value. However, according to the previous analysis, for the silty clay of Tianjin, until the temperature reaches -7 ℃, the content of the unfrozen water will not have a significant change and increase. However from the observation of the corresponding time, it can be concluded that until the soil sample temperature reach 7℃, grayscale value is still increasing which illustrates that not only the increase of unfrozen water content can cause the increase of CT image grayscale value, but also the rise of frozen soil temperature can cause the increase of grayscale value of soil sample CT image.

CONCLUSION

In this paper, on the basis of studying related technology of CT scanning [10], the following conclusions are obtained through the analysis of experiment results: in the process of melting and temperature rise of the frozen soil, the grayscale means increase obviously with the time. After the completely melting of the frozen soil, although the temperature is still rising, the grayscale mean does not change significantly. Therefore, at the moment of the completion of the frozen soil melting, a clear break point appears on the time - grayscale image which can be seen as a sign of the completion of the frozen soil melting.

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