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Measuring Method Study on Unfrozen Water Content of Frozen Soils

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Abstract

This paper illustrates the progress of experimental measurement methods and theoretical prediction models on unfrozen water content of frozen soils. And compared and summarized various measurements. Besides, the experimental principles and characteristics of measuring method which include temperature measurement, calorimetric, CT image, TDR and NMR are analyzed. It is found that a single test method cannot establish the coupling model between unfrozen water content and relevant influencing factors such as time, temperature, soil property and confining pressure conditions, but NMR is a fast, accurate and nondestructive method to test unfrozen water content, which has a good application and development prospect compared with other methods. Combined with the existing theoretical prediction model of unfrozen water content, it is found that due to the large difference of soil properties, there are some errors in the comparison between the predicted data of the model and the measured data. What's more, the test technology of unfrozen water content in frozen soil is prospected.

Keywords

Frozen soil; unfrozen water content; measuring method.

1. Introduction

The frozen soil refers to a kind of soil and rock with a temperature below 0 ℃ and containing ice, which is a porous multiphase system composed of soil particles, unfrozen water, ice and gas[1]. In China, frozen soil is widely distributed, which leads to a research hotspot of frozen soil application in our country. In recent years, in the process of engineering construction in frozen soil areas, more and more problems such as frost heave, thaw settlement, grouting, salt heaving, salinization restrict the development of resources and the sustainable development of economy seriously.

Unfrozen water and soil particles, gas and ice which exist in frozen soil formed a multiphase complex system and sensitive to temperature. In the process of soil freezing, due to the decrease of temperature, the content of unfrozen water in soil decreases, while the content of cemented ice increases, resulting in the overall strength of frozen soil increases with the decrease of temperature [2]. On the contrary, in the process of melting, due to the increase of temperature, the content of unfrozen water increases and the content of ice decreases, the cementation between soil particles disintegrates sharply, the structural stability of soil decreases, and the overall strength decreases.

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2. Testing and Measurement Methods

Adopting the experimental method to measure the unfrozen water content in frozen soil is an important means to study the frost heave of soil. It can be summarized as follows:

2.1. Temperature measurement method

The data measured by the temperature measurement method [3] are based on the initial water content corresponding to a certain initial freezing temperature, and then draw the double logarithmic relation curve between the unfrozen water content and the temperature. The principle is that the heat of crystallization is released and the temperature change of soil sample is caused by the sudden change of temperature due to the release of the heat of crystallization when the phase transformation of water occurs. When the crystallization is formed and developed, which will release the heat of crystallization and cause the change of soil sample temperature. As the time of temperature reaches the highest value and unstable, it is the initial temperature of the soil, which corresponds to the initial unfrozen water content.

The biggest advantage of this method are simple and easy, but it cannot reflect the continuous process of unfrozen water content in frozen soil , when the changes of temperature happened, which means some certain error would exist.

2.2. Near infrared spectroscopy

Near infrared spectroscopy (NIR) is applied to measure the unfrozen water content of frozen soil by using temperature sensor, moisture sensor and near infrared spectrometer[4]. Due to the substances have different spectral curves, the content of unfrozen water could be measured by near infrared spectrometer. The wavelength range of near-infrared light is 800-2500nm, and the absorption spectral frequency of water molecules has five absorption bands. Using these frequency information to set a reasonable and central wavelength of the absorption band (around 760, 970, 1145, 1450, 1940nm) as the detection wavelength of unfrozen water, the information of absorption wavelength of unfrozen water to near-infrared light in frozen soil can be analyzed[5].

This method has many advantages of less external interference, shorter time for a single test and environmentally friendly. However, this method could only measure the unfrozen water content on the surface of frozen soil, but cannot measure the change of unfrozen water content and ice content in permafrost.

2.3. CT image method

CT technology, also known as computer tomographic recognition technology, is a method to obtain the digital image of the detected object through projection reconstruction, which is based on the principle of interaction between radiation and matter [6]. CT technology has been widely used in permafrost research because of its non-damage. Wang Li et al [7] used CT technology to study the difference of freeze-thaw damage of red sandstone under different initial saturated states. Ming Feng et al [8] quantitatively analyzed the damage degree of soil freeze-thaw cycle through the change of CT number, and then reflected the change of permafrost structure. Song Yongjun et al [9] scanned red sandstone under uniaxial loading CT in real time, and analyzed the macroscopic mechanical properties and damage evolution mechanism of rock.

Although CT nondestructive testing does not destroy the integrity of test samples and reflect the changes of microstructure in frozen soil truly, its image resolution and accuracy are relatively low.

2.4. Time domain reflectometer method

The principle of time domain reflectometer (TDR) is that electromagnetic pulse waves are emitted in the TDR and transmitted into the soil through the probe, then the dielectric constant of the soil can be obtained by measuring the time when the electromagnetic wave propagates in the soil through the probe and reflected at its end. However, the dielectric constant of different proportions of water in a certain volume of soil is different, resulting in different propagation velocities of electromagnetic waves, and water content can be judged by different propagation velocities of electromagnetic waves[10].

However, the dielectric constant of soil is easily affected by physical factors such as soil quality, temperature, bulk density and so on[11-12]. As a result, deviation is easy to occur when this method is adopted.

2.5. Nuclear magnetic resonance method

Nuclear magnetic resonance (NMR) [13] is a high-resolution nondestructive detection technique for studying the content and distribution of protons (hydrogen nucleus 1H) in a unit volume medium, which mainly uses the energy change of the nucleus in the magnetic field to obtain the information about the nucleus. Nuclear magnetic resonance T_2 curve can be used to measure the nuclear magnetic intensity amplitude and relaxation time of pore water in different positions in soil, and the content of unfrozen water in frozen soil can be obtained quickly and accurately[14-15].

Although the NMR method cannot continuously collect the signal strength and temperature at the same time, the testing time cost and cost are high, and it is easy to be affected by metal material or small current. However, NMR is direct and non-destructive, less disturbed by external interference, and the time for a single test is shorter and will not disturb the sample. Therefore, this method is a rapid, accurate and non-destructive method for the determination of unfrozen water content, and has a good application and development prospect.

3. Theoretical Prediction Model

In addition to the above test methods, a series of models which could predict the unfrozen water content in permafrost have been proposed. Tice [16] determined the values of α and β parameters in the proposed exponential formula by testing the specific surface area of clay particles. The empirical formula of unfrozen water content is as follows:

$$w_u = \alpha T^{\beta}$$

Where w_u is the content of unfrozen water, α and β are the empirical characteristic parameters of soil, and T (℃) is the absolute value of negative temperature.

Based on the exponential relationship between unfrozen water content and temperature, according to the initial moisture content and the corresponding freezing temperature, a method for quickly determining unfrozen water content was put forward by Xu xuezu[1].The formula is as follows:

$$w_u = w_0 \theta_f^b \theta^{-b}$$

Where w_u is the content of unfrozen water, w_0 is the initial water content, b is the empirical constant related to the soil quality factors, θ is the negative temperature absolute value, and θ_f is the initial freezing temperature absolute value. Besides, the initial water content is appropriate to between the liquid limit and the plastic limit.

In addition, there are still many effective models for predicting unfrozen water content. Michalowski[17] simulates the change of unfrozen water content by establishing a prediction model related to soil freezing temperature, maximum unfrozen water content without free

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water, minimum unfrozen water content. Based on the prethawing theory of porous media, Wan Xusheng et al[18] proposed a method for calculating the content of unfrozen water in soil, and its rationality is verified by experimental data.

4. Summary and Conclusions

Based on the related problems of the unfrozen water content in frozen soil, this paper analyzes the research status of the measurement methods of unfrozen water content in frozen soil from the experimental means and theoretical prediction model respectively. It is found that a single test method cannot establish a model of coupling unfrozen water content with time, temperature, soil quality, confining pressure and other related factors. At the same time, the relevant empirical parameters in the prediction model of unfrozen water content are closely related to the properties of the measured soil, while there are many kinds of soil in nature and there are great differences among soil properties. The influence of empirical formula or prediction model on the empirical parameter control of soil will cause a big error when comparing the predicted data with the measured data in the later stage.

With the rapid development of modern technology, looking forward to the future research work of unfrozen water in permafrost, it is expected to make breakthroughs in the following aspects:

(1) The NMR nuclear magnetic resonance method should be further improved, and make it to be a fast, accurate and economical measurement method.

(2) A more accurate prediction model of unfrozen water content with less proportion controlled by empirical parameters should be established.

(3) In-situ testing technology and quality technology of unfrozen water content in frozen soil should be further studied.

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