

STUDY OF THE RELATIONSHIP BETWEEN THE UNFROZEN WATER CONTENT OF FROZEN SOIL AND PRESSURE

Zhang Lixin¹, Xu Xiaozu, Deng Yousheng¹, Zhang Zhaoxiang²

1. State Key Laboratory of Frozen Soil Engineering, Lanzhou Institute of Glaciology and Geocryology,
Chinese Academy of Sciences, Lanzhou, 730000, P.R. China
e-mail: lxzhang@ns.lzb.ac.cn

2. Beijing Agriculture University, Beijing, 100086, P.R. China

Abstract

The relationship between the unfrozen water content and pressure is important in studying the physical properties and mechanical behaviors of frozen soils under high pressure. We have designed an apparatus to determine the unfrozen water content of frozen soil at high pressures using a Nuclear Magnetic Resonance probe. The unfrozen water contents were determined at temperatures from 0 to -20°C, and pressures from 0 to 40 MPa. The experimental results show that the freezing point of soil decreases linearly with increasing pressure and that the unfrozen water content of frozen soil increases with increasing pressure in a non-linear manner.

Introduction

A mixture of soil and water is a very complex system. Adding ice in frozen soils makes it even more complex. The study of the properties of the water film surrounding the soil grains, and the equilibrium between ice and water, is of great significance in further understanding these systems. One of the important properties of water in frozen soil is the relationship between unfrozen water content and pressure. Unfrozen water content is related to the freezing point of the soil-water system and has been studied since the 1960's in Russia and the 1970's in China. However, until now, the study results have been limited because of the lack of suitable experimental methods. Early results mainly focused on the changes in the freezing point of soil under different pressures. Little has been reported on the relationship between the unfrozen water content and pressure.

At the beginning of the 1990's, guest researchers at the State Key Laboratory of Frozen Soil Engineering, Institute of Glaciology and Geocryology, used a resistivity freezing-point meter to study the unfrozen water content. This method depends on the change in resistivity of the soil-water system, before and after freezing, and was used to determine the frozen or unfrozen states of clay, sandy clay and sand in a range of pressures from 0 to 8 MPa. The resistivity and temperature data were used to determine the freezing point (Cui and Li, 1993).

In the mid 1990's, we found an industrial ceramic that is used to make high strength test tubes. The tubes can support high pressure and are suitable for use with the Nuclear Magnetic Resonance (NMR) method for determining unfrozen water content of frozen soil under high varying pressures. The pressure is applied using a mechanical loading system.

There are many mineral resources, covered with deep Quaternary surface soil layers, in areas of northeastern, northern, eastern and central China. The depth of these minerals can reach 600 m in some areas. The development of mines in these areas often requires the use of artificial freezing to strengthen the walls of the mine shafts and to control the inflow of ground water. This technique was first used in 1955 at the Kailuan coal mining area in Hebei Province.

The strength and stability of frozen shaft walls are directly related to the success or failure of the freezing process. The thickness of frozen walls depends on the requirements for overall strength and stability. Thus, the thickness of the frozen walls becomes a key element in engineering design and construction.

The 0°C isotherm is still regarded as the boundary of the frozen wall during design and construction (Cui and Li, 1993). However, the freezing point is lower than 0°C when a soil is subjected to pressure. This results in the frozen walls being thinner than recommended in

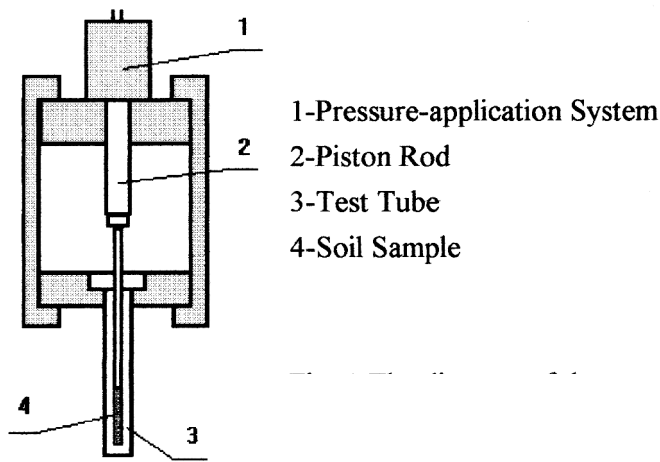


Figure 1. Diagram of the experimental installation.

the design with the possibility of engineering failure. Additionally, different soil types have different strengths at the same subfreezing temperature because of differences in unfrozen water contents. Thus, it is important to determine the relationship between pressure and unfrozen water content.

The study of the relationship between unfrozen water content and pressure provides information on the dynamics of unfrozen water. It also provides an experimental basis in order to verify existing theories. Forecasting models of unfrozen water content lack an experimental basis to directly apply the Clapeyron Equation in frozen soils. This paper attempts to experimentally define the relationship between unfrozen water content over a range of overburden pressures.

Experimental installation and sample preparation

EXPERIMENTAL INSTALLATION

The equipment used in this experiment is a Nuclear Magnetic Resonance (NMR) probe. A self-designed mechanical pressure-application system, with a non-metallic test tube was constructed. The bottom part of the piston rod of the pressure-application system is made of brass. The test tube is made of ceramic materials. These two materials are used to prevent the magnetic field of the NMR probe from being disturbed during the test. The internal and external diameters of the test tube are 10 mm and 25 mm, respectively, meeting the requirements of the NMR probe. The designed

maximum pressure is 50 MPa. The diameter of the piston rod applying the pressure is 20 mm, twice the internal diameter of the tube. Using this ratio, the application of 1 MPa of pressure provides 4 MPa of overburden pressure to the soil sample in the tube. A diagram of the experimental installation is shown in Figure 1.

SAMPLE PREPARATION

The soil used in this test is Lanzhou loess. Its basic physical properties are listed in Table 1. The soil was crushed and then sieved. The dry soil was mixed with distilled water to provide samples with a predetermined initial water content. The soil sample was placed in the test tube and compressed to make it solid and to reduce the amount of air in it as much as possible. Preliminary study results indicated that the density of frozen soil has little influence on the unfrozen water content. For example, the unfrozen water content of Morine clay, with initial water content of 19.3% at a temperature -1.0°C increased by less than 1.0% when the density was increased from 1.0 g/cm^3 to 1.71 g/cm^3 (Xu and Deng, 1991). This conclusion is presumed to apply to this experiment because the density of the test sample increases with increasing pressure.

The Clapeyron Equation describes the two-phase equilibrium for a single material. The equilibrium between pure water and ice at a certain temperature and pressure, can be expressed as the following simple equation:

$$dT_f = 0.075dP \quad [1]$$

where dT_f ($^{\circ}\text{C}$) and dP (MPa) are the change in the freezing point of water and the change in the pressure respectively. This equation implies that phase equilibrium can be maintained by corresponding changes in dP and dT_f . A change in pressure influences the freezing point of water in a linear manner. The purpose of this experiment was to test the phase equilibrium of water in frozen soil subject to various overburden pressure. Pressure was applied to the system at 0, 2, 4, 6, 8, and 10 MPa; the corresponding pressures on the sample in the test tube were 0, 8, 16, 24, 32 and 40 MPa, respectively. A constant pressure was maintained at every pressure stage while determining the unfrozen water contents of the frozen soil at different negative temperatures.

Table 1. Basic physical properties of Lanzhou loess

Soil	Grain size (mm) composition (%)				Physical Properties		
	>0.1	0.1-0.05	0.05-0.005	<0.005	$W_p(\%)^1$	$W_L(\%)^2$	Salinity(%)
Lanzhou Loess	0.48	7.13	75.69	16.70	17.60	26.70	0.08

¹Plastic limit; ²Liquid limit.

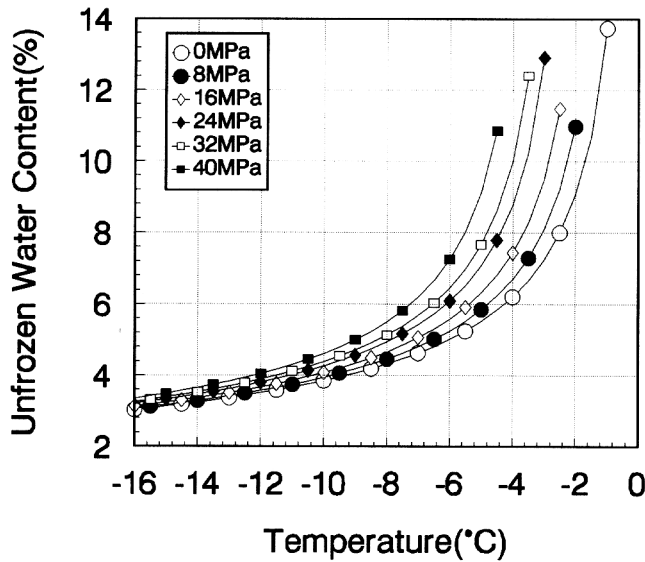


Figure 2. The unfrozen water content of frozen Lanzhou loess corresponding to different pressures and temperatures.

Results and analyses

Figure 2 shows the unfrozen water content of Lanzhou frozen loess corresponding to the different pressures and temperatures. It was found that the unfrozen water content increases with increasing pressure. The relationship between the unfrozen water content and the pressure, at a certain temperature, can be expressed by the following equation:

$$W_u = P / (AP + B) \quad [2]$$

where W_u is the unfrozen water content (%), P is pressure (MPa), and A and B are parameters related to the soil type.

Using the relationship between unfrozen water content and temperature, the freezing points of Lanzhou loess, with the same initial water content and under different pressures, have been calculated. The results are shown in Figure 3. It is clear that the freezing point decreases in a linear manner with increasing pressure. The slope is approximately $-0.075^\circ\text{C}/\text{MPa}$ and it coincides with the calculated results using the Clapeyron Equation.

In the earlier studies an Overlapping Principle (Xu *et al.*, 1995) concerning the freezing point of the soil-water system was advanced. That principle states that the freezing point (T_f) is a function of initial water content (W), the type of salt (N), salinity (C) and pressure (P) for a certain type of soil.

$$T_f = f(W, N, C, P) \quad [3]$$

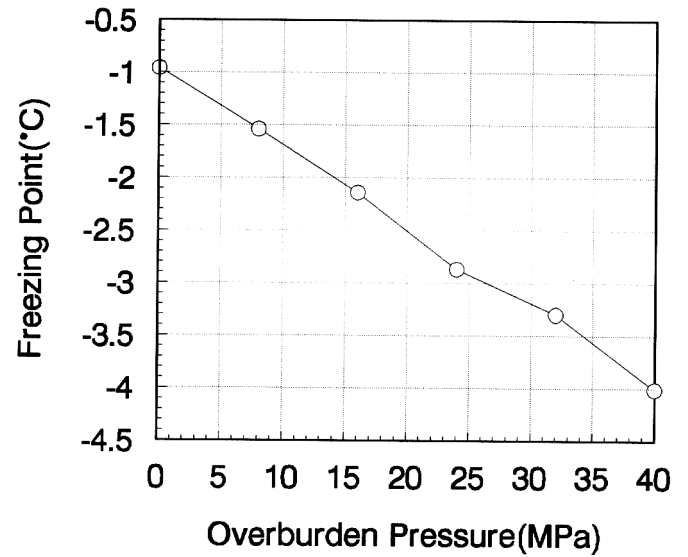


Figure 3. The freezing point of soil water system under different pressures.

The contribution of every factor to the freezing point is additive, although each factor's influence on the freezing point is independent. On the basis of this principle, a forecasting model for unfrozen water contents was erected (Xu *et al.*, 1995). However the relationship between the unfrozen water content, or the freezing point and the pressure was not directly tested due to limitations of the experimental method. This paper advances the conclusion that the Clapeyron Equation can be used directly in the forecasting model. It has the advantage of improving the precision of the model for the unfrozen water content, or the freezing point, relationship to pressure.

Conclusions

- (1) The unfrozen water content of frozen soil increases with increasing pressure. The freezing point of the soil-water system decreases in a linear manner with increasing pressure and this relationship can be described by the Clapeyron Equation.
- (2) The water in soils has the same properties as free water in the aspect of the phase equilibrium relationship to temperature and pressure.
- (3) The data improves the application of the Overlapping Principle (Xu *et al.*, 1995) to the freezing point of soils.

Acknowledgments

This project was supported by the National Natural Science Foundation of China, No. 49401003.

References

- Cui Guangxin and Li Yi** (1993). The primary study on the freezing point of soil water system. *Glaciology and Geocryology*, **15**, 317-321 (In Chinese).
- Xu Xiaozu and Deng Yousheng** (1991). The experimental study of water migration of frozen soil. Science Press (In Chinese).
- Xu Xiaozu, Wang Jiacheng, Zhang Lixin, Deng Yousheng, Taozhaoxiang** (1995). *Mechanism of freezing heave and salt heave of soils*. Science Press (In Chinese).