I. Introduction

When ground freezes in cold region, water is induced to flow towards the freezing front as lenses form and frost heave occurs. Frost heave damages roads, buildings and irrigation-drainage systems in a farmland. To overcome such frost-action damages, it is necessary to clarify frost heave mechanism.

Many researchers have studied the frost heave mechanism. For instance, Miller [1)] proposed a model which is based on heat and mass transport through a partially frozen zone called frozen fringe. Introducing the concept of segregation potential, Konrad [2)] proposed a frost heave model which is based on the observation that the velocity of water intake is proportional to temperature gradient in the frozen fringe. These models have emphasized the importance of the frozen fringe. The frozen fringe is assumed to consist of unfrozen water, soil particles and a network of pore ice extending from the base of the active ice lens[3)]. However, few experimental studies have been carried out to clarify actual structure of the frozen fringe. In this paper, we report an experimental study on microstructure near the freezing front observed with a microscope in 10 μm scale-resolution during soil freezing.

Table1 Sample Velocity Vs (μm/sec) and temperature gradient α (°C/mm)

Vs \ α	0.2	0.125
0	A0	B0
0.4	A1	B1
0.6	A2	B2
0.8	A3	B3

II. Experimental Method

The soil used here was Fujinomori clay. The soil consisted of 15% sand , 61% silt and 24% clay. The dry density of the soil is 1.18 g/cm^3. The specific surface area of the soil is 24.5m^2/g. The soil was mixed with distilled water to make slurry and deaired by a vacuum pump. The slurry was placed in an acrylic cylinder with 10 cm diameter and was consolidated at an overburden pressure of 1 MPa for a week. A 3 mm-thick rectangular sample was obtained by cutting the consolidated soil and placed between a pair of microscope slide glasses as shown in figure 1. The sample cell had a water reservoir at the warmer side to supply water into the freezing front. Both sides of the sample cell were sealed with glue to keep saturated condition. Vaseline was applied to the slide

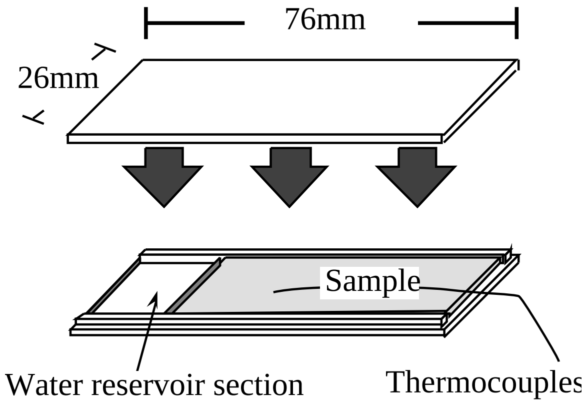

Fig.1 Schematic diagram of sample cell for direct observation

glasses to reduce friction between soil and glass. Two copper-constantan thermocouples were inserted into the sample cell for the measurement of temperature. The sample cell was lighted up by using a cold light during the experiment.

A schematic diagram of our experimental apparatus is shown in figure 2. The sample cell was placed in a teflon cell holder indicated by a star mark ; ☆. The temperature of each end of the sample cell was controlled by thermo electric cooling devices. Thus during the experiment, a constant temperature gradient, α, was maintained. The sample cell holder was moved toward the cold side at a constant velocity from 0 to 40 μm/sec by a computer-controlled pulse motor. Eight series of experiments were conducted with two different temperature gradients and four different sample velocities, Vs. When Vs was zero, the isotherms moved immediately after lowering the temperature at cold side. When Vs was not zero, the freezing velocity, Vf, was equal to the sample velocity, Vs. The experimental conditions on temperature gradients at steady state and sample velocities are shown in table 1.

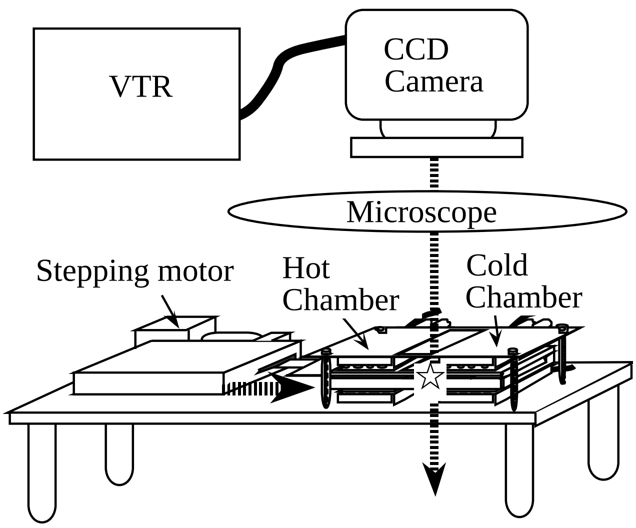

Fig.2 Schematic diagram of direct observation apparatus

During each experiment, the apparatus was located in the ambient temperature of 5.0 ℃; so that the initial temperature of the sample was 5.0 ℃. Each observation was made after a constant temperature gradient was given to the sample for one hour. Ice segregation and crystal growth near the freezing front were observed with a microscope (40 magnification). The microscope was equipped with a charge coupled device (CCD) camera and a video system. Sample images were captured in one-minute interval. The sample images was divided with 20 μm mesh by a computer and the crystal growth rate was measured from a relative coordinate of the growing surface. And the temperature of ice segregation was determined by tracing the measured temperature profiles on the image.

III. Experimental Results

(1) Freezing experiment with zero sample velocity (A0 and B0)

Figure 3 shows an image of the freezing process in the condition that sample A0 at a velocity of 0 μm/sec and a temperature gradient of 0.2 ℃/mm. It was observed that ice lenses segregated rhythmically from the cold side and that the warmest ice lens was formed at a point below the 0 ℃ isotherm. Neither pore ice larger than 10 μm nor a displacement of soil particles was found in the region between the warmest ice lens and 0 ℃ isotherm. The warmest ice lens started to segregate at -0.55 ℃ and grew 1.7 mm-thick during time period of 400 minutes. The temperature at the interface between the warmest ice lens and soil particles increased gradually and reached -0.2 ℃.

Figure 4 shows the change in thickness of the warmest ice lens with time for specimens A0 and B0. Specimen A0 was frozen at a larger temperature gradient than specimen B0 (see Table 1). The elapsed time was counted from start of

Fig.3 Image of Fujinomori clay in freezing process for A0

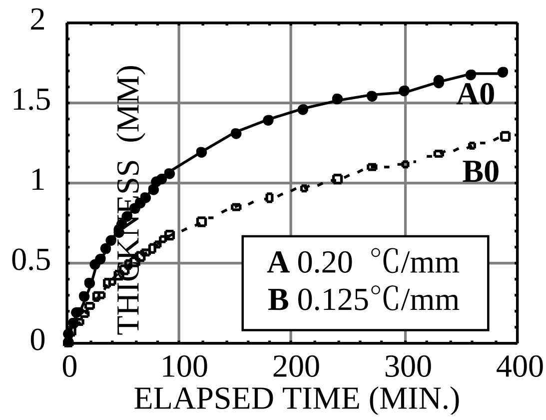

Fig.4 The relationship between the thickness of the warmest ice lens and time

segregation of the warmest ice lens. The warmest ice lens grew rapidly in the beginning, and grew more slowly at later time stages. After 400 minutes, a thicknesses of warmest ice lenses were 1.7 mm and 1.3 mm for A0 and B0, respectively. These results indicate that the thickness of ice lens increase more at the larger temperature gradient and that the growth of ice lens stabilized with time. The difference in the thickness of ice lens between A0 and B0 came from the difference in the growth rates in the early stages of the experiment.

Figure 5 shows temperatures at the growth surface of the warmest ice lens. The temperatures increased with time and were gradually approaching -0.2 ℃. The temperatures at which the warmest ice lenses started to form were -0.55 ℃ and -0.4℃ for A0 and B0, respectively. When the temperature gradient was steeper, the warmest ice lens started to form at a lower temperature.

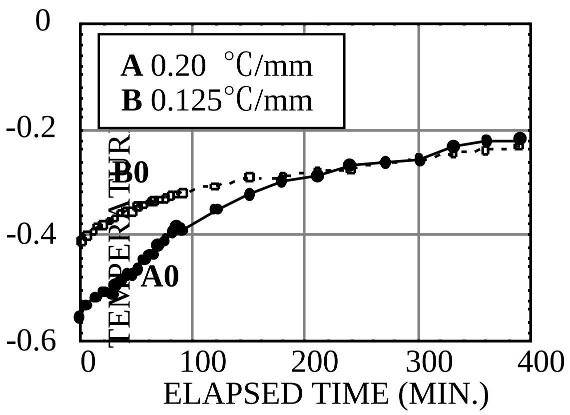

Fig.5 Temperature at growth surface of the warmest ice lens as a function of time

Figure 6 shows growth rate of the ice lenses at the growth surface of the warmest ice lens as a function of temperature. The results in Fig. 6 were obtained from 7 experiments at conditions A0 and 3 experiments at conditions B0. No ice lenses grew at temperature above -0.2 ℃. This indicates that the growth rate of ice lens is determined by the temperature at the growth surface. These results agreed well with the result reported by the Ishizaki et al.[4] .

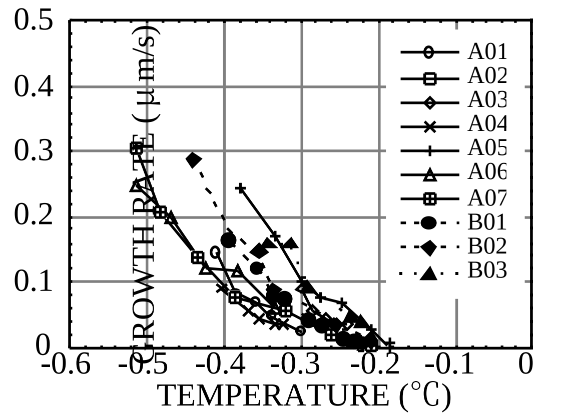

Fig.6 The relationship between growth rate of the warmest ice lens and temperature at the growth surface

(2) Freezing experiments with different sample velocities (A1 to A3 and B1 to B3)

Figure 7 shows an image of freezing process for a sample which was moving at a velocity of 0.6 μm /sec towards the freezing element at a temperature gradient of 0.2 ℃/mm (condition A2). Rhythmic ice lenses were observed near the freezing front during freezing. In this series of experiments, each ice lens was formed in a similar interval and had similar thickness. Once a new ice lens segregated on the warm side, previously formed ice lenses stopped growing. This ice lens also stopped growing when a more recent ice lens started to segregate on the warm side. In the case of A2, the segregation and the growth of ice lens were observed at -0.5℃.

Fig.7 Image of Fujinomori clay in freezing process with applying a sample speed (A2)

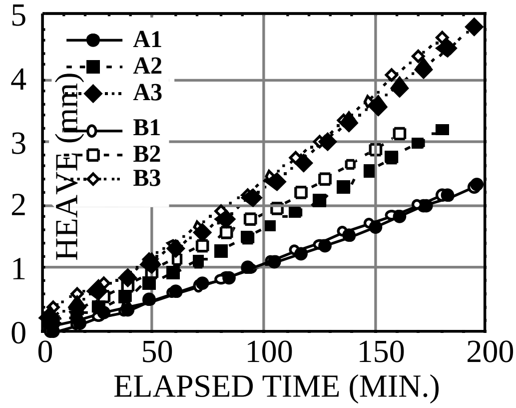

Fig.8 Total heave when the sample was moved

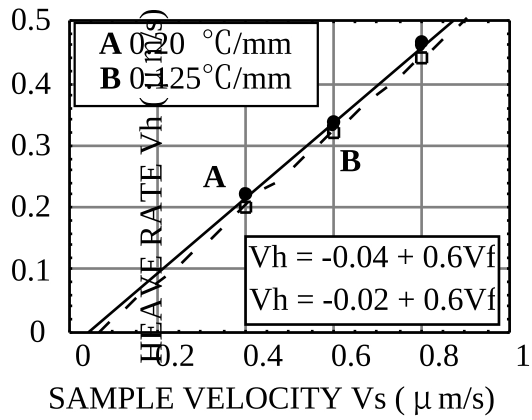

Fig.9 The relationship between frost heave rate and sample velocity

Figure 8 shows total heave as a function of time for different sample velocities. The total heave was determined by movement of a soil particle on the sample images. In this series, the elapsed time was counted from the start of the sample cell movement. Heave increased linearly with time for each specimen. The total heave increased with increasing freezing velocity.

Figure 9 shows relationship between heaving rate and sample velocity. The solid line is the best fit for the experimental values for series A (α = 0.2 ℃/mm) and the dashed line for series B (α = 0.125 ℃/mm).

Figure 10 shows the segregation temperature for the ice lenses. The segregation temperature is here defined as the temperature of the interface at which an ice lens is growing. Each ice lens started to segregate at a constant temperature. When the freezing velocity and the temperature gradient were high, ice lens segregated at a lower temperature. These results indicate that the segregation temperature was dependent on the freezing velocity than the temperature gradient.

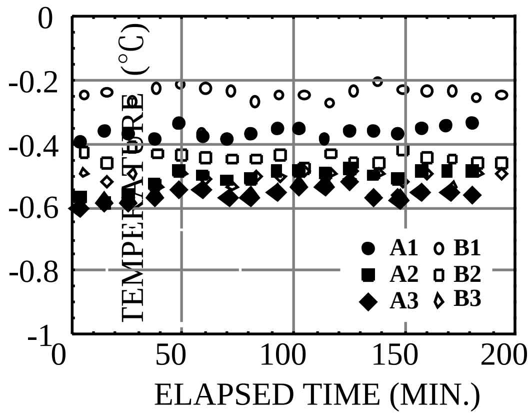

Fig10 Temperature at growth surface of ice lens

IV. Discussions

We will discuss here a frost heave model by using the experimental results. At first, we examine the frost heave model based on a partially frozen zone, so called frozen fringe.

In the frozen fringe model, frost heave is determined by the coupled of heat and water flow in the frozen fringe. Soil water would flow through the frozen fringe with permeability coefficient, K, from the unfrozen zone to the surface of the growing ice lenses due to the pressure gradient, dP/dx. If all water flowing to ice lens contributes to the warmest ice lens growth, the growth rate of the warmest ice lens, Vg, is given by

$$V_g = - \frac{K}{\rho_i g} \frac{dP}{dx} , \tag{1}$$

where ρ_i is the density of ice and g is the gravitational constant. Gilpin [3] and Nixon [5] have assumed that pore ice would grow so that unfrozen water content would decrease. They have expressed the permeability of the frozen fringe, K, as a function of temperature:

$$K = \frac{K_0}{(-T)^{\alpha}} , \tag{2}$$

where K_0 is the permeability of frozen ground at -1 ℃, T is the temperature in the frozen fringe and α is an empirical constant. Equation (2) means that the permeability of the frozen fringe decreases exponentially with decreasing temperature of the frozen fringe. Consequently, the growth rate of the warmest ice lens calculated by eq. (1) should decrease.

In our experiment, the growth rate of the warmest ice lens decreased with increasing temperature at the growth surface of ice lens as shown in figure. 6. The experimental result corresponds to not the frozen fringe model by Gilpin and Nixon but the experimental results by Vignes et al.[6] , Biermans et al.[7] and Ozawa et al.[8] . This discrepancy may come from the postulation that there would be pore ice in the frozen fringe. Actually, we did not observe any pore ice larger than 10 μ m could be observed (e.g. figure. 3, figure. 7).

If we assume that there is no pore ice in the frozen fringe, the frozen fringe has a constant permeability and the soil water flows to the surface of growing ice lens through the frozen fringe due to a temperature difference. By applying generalized Clausius-Clapayron equation, pressure of the soil water on the growth surface of ice lens is given by

$$\Delta P = 1.23(T_s - T_m) + 0.11\Delta P_i + \Pi \quad [\mathrm{MPa}]^{9)}, \quad (3)$$

where ΔP is the pressure difference between the soil water and an atmosphere, Ts is the temperature at the growth surface of ice lens and Tm is the melting point of ice at an atmospheric pressure, ΔPi is the pressure difference between ice lens and the atmosphere, and Π is the osmotic pressure of the soil water. For soil freezing without overburden pressure, ice pressure in the soil may be at the atmospheric pressure. In addition, the osmotic pressure may be negligible for salt free soil. Then eq. (3) becomes

$$\Delta P = 1.23(T_s - T_m) \quad [\mathrm{MPa}]. \quad (4)$$

This equation means that the pressure difference can be expressed as a linear function of the temperature at the growth surface of ice lens. If it is assumed that the hydraulic conductivity of the frozen fringe and kinetic coefficient at the growth surface of ice lens are constant, the calculated ice lens growth rate would increase with decreasing the temperature at the growth surface of ice lens. This relationship between the growth rate and the temperature is consistent with our experimental results in figure 6. Nevertheless the ratio calculated from eq. (4) is one order larger than our experimental result. To explain the difference between the calculation and the experiment, two possibilities can be considered; one is that hydraulic conductivity of soil between 0°C isotherm and growth surface of ice lens might be 1-order lower than that of unfrozen soil, and the other is that an unfrozen water film on the growth surface of ice lens would have some resistance to supply water into ice crystal. The former possibility may come from either the viscosity of water affected by local changes of temperature, pressure and solute concentration or the clogging of pore by bubbles which would be formed on interface. This possibility, however, will be low because frost heave was observed in the experiment using deaired pure water and glass beads. The latter possibility will come from kinetic process during interface growing. The kinetic process is a process which deals with a dependence of molecular incorporation to an interface on the interface growth rate. The interface kinetics is one of the fundamental factors which decide a crystal growth shape.

For the discussion of the kinetic process in frost heave, however, more studies will be needed considering non-equilibrium process. In any possibility, our experimental results indicate that the ice segregation rate is determined by the kinetic process at the segregating surface rather than the hydraulic conductivity in partially frozen zone (frozen fringe).

V. Conclusions

Microstructure near freezing front during soil freezing was observed directly by using an one dimensional freezing apparatus. From the experiments, the following results are obtained; (1) No pore ice was formed in the frozen fringe. (2) The frost heave depends on the freezing velocity. (3) The heaving rate depends on the temperature at the growth surface of the warmest ice lens. (4) The temperature of ice lens segregation depends on the freezing velocity.

It was concluded that the temperature at the growth surface of the warmest ice lens is an important factor for the frost heave mechanism. We will need more studies on the microscopic process near the freezing front to clarify the frost heave mechanism.

Acknowledgments

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