Microscopic Observation of Ice Lensing and Frost Heaves in Glass Beads

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Abstract

Frost heave in soil is a complex solidification phenomenon which involves movement of water through unfrozen soil to the freezing front. In order to clarify the frost heave mechanism, microscopic ice lensing in glass beads has been observed by using an apparatus which can control the temperature gradient and freezing velocity independently. As a result, it was found that artificial ice lenses were formed in the glass beads as well as soil and that thickness of the ice lenses depended on freezing velocity. In addition, exclusion and encapsulation of glass beads particles have been observed in freezing water-particles systems by using the same apparatus. The results suggest that particle size and freezing velocity are important factors for ice lensing. Observing the ice lensing microscopically will help to understand the mechanism of frost heave.

INTRODUCTION

Frost heave occurs when ice formation segregates the soil structure. This process is called ice lensing. Although a lot of models and theories about the frost heave (eg. Miller, 1978; Konrad and Duquennoi, 1993; Gillpin, 1980) have been proposed, details of the mechanism remain unknown. Frost heave in soil is a complex solidification phenomenon that is caused by various water-related factors. Soil is so heterogeneous in terms of texture, particle shape, electrical charge and chemical composition that it is difficult to clarify which is important for ice lensing. Because of this soil complexity, few microscopic observations have been carried out to visualize ice lensing.

Ice lensing is known to occur in some porous media (Ozawa and Kinosita, 1989; Wilen and Dash, 1995). If frost heave in an ideal porous medium is observed directly, it would be helpful to reveal the factors responsible for frost heave. There are two types of ice growth in the water system containing a few foreign particles; one is ice growth that encapsulates the particles and the other is ice growth that pushes the particles ahead. The criteria of the ice formations in the system are affected by interaction between the ice growing surface and a particle (Uhlmann and Jackson, 1966; Körber et al., 1992). From the view point of the exclusion of particles, the ice lensing in porous media may belong to the latter ice growth. Therefore, it is valuable to compare the ice lensing in a porous medium to the ice growth which excludes foreign particles in the water system.

In this study, we observed ice lensing in glass beads instead of soil through microscope by using a directional freezing apparatus (Somboonsuk, Mason and Trivedi, 1984) which can control a temperature gradient and a freezing velocity independently. And we observe isolated particles near ice growing surface by using the same apparatus. Then, we discuss influence of temperature gradient, freezing velocity and particle size on frost heave.

METHODS

Directional Freezing Apparatus

A directional freezing apparatus (Somboonsuk, Mason and Trivedi, 1984) is schematically shown in Figure 1.

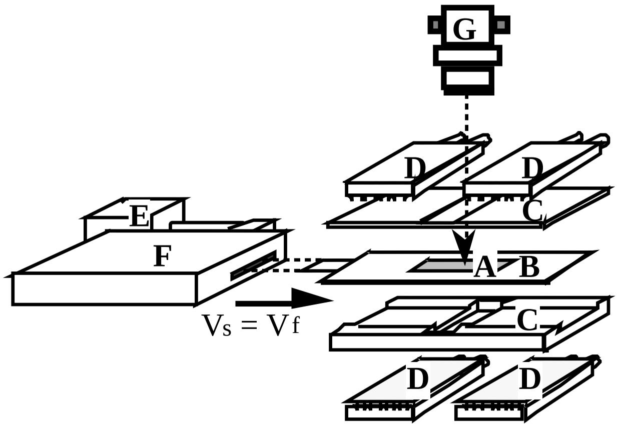

Figure 1. Experimental apparatus
Freezing velocity, V_f, and temperature gradient A, are controlled independently. A: sample cell, B: teflon cell holder, C: copper blocks, D: thermo-electric devices, E: computer-controlled pulse motor, F: translational stage

A sample, illustrated as the shaded portion, was placed in a teflon cell holder. To give a temperature gradient to the sample cell, each end of the sample was held at different temperatures, T_H and T_L, by two copper blocks kept at constant temperatures by thermo-electric devices. The cell holder connected to a translational stage with a computer-controlled pulse motor was moved at a constant velocity, V_s. Ice lensing and ice-water interface were observed through a microscope which was equipped with a charge coupled device (CCD) camera and a video tape recorder (VTR) system. Sample images were captured in one-minute interval and analyzed to measure the rate of ice lensing.

Materials and Experimental Conditions

Two kinds of in situ observations were made. One was the observation of ice lensing in the glass beads contacting each other (packed particles system) and the other was the observation of pushing or encapsulating the glass beads dispersing in water (isolated particles system).

PACKED PARTICLES SYSTEM

The sample used here was glass beads with the diameter of 2.2 µm. The glass beads were mixed with distilled and deaired water at the water content of 80% by weight and compacted in a sample cell with 3 mm thickness. The cell was composed of a pair of 26 x 76 x 1 mm^3 slide glasses and a spacer.

When the different temperatures were given to each end of the sample cell, the isotherm advanced in the sample until a steady state was attained. We made two types of freezing experiment.

In the first experiment we observed the vicinity of a growing ice lens immediately after temperature gradient was applied until the warmest ice lens stopped growing. The final temperature gradients given to the cell are shown in Table 1.

Table 1 Experimental conditions for packed particles system

A (°C/mm)	V_f (µm/s)	
	Exp. 1	Exp. 2
0.20	-*	0.4 0.6 0.8
0.28	-*	0.4 0.6 0.8
0.33	-*	0.4 0.6 0.8

A: Temperature gradient,
V_f: Freezing velocity, *:V_s = 0 (µm /sec)

In the second experiment, after a temperature gradient was given to a sample cell for 1 hour, the cell was moved toward cold side at the constant velocity of V_s. Since the advancing velocity of the isotherm had decreased rapidly to low enough for 1 hour, the cell velocity of V_s gave a constant freezing velocity, V_f, to the sample ($V_f = - V_s$). We observed the vicinity of ice growing surface for a duration until the cell was moved by 20 mm distance. The condition on the temperature gradient at steady state, A, and freezing velocity, V_f, are shown in Table 1.

ISOLATED PARTICLES SYSTEM

The sample used here was three types of glass beads with different diameter, 2.2, 5.3 and 9.7 µm. Each sample was a mixture with the water content of 1000g-water per 1g-glass beads. The mixture was compacted in a sample cell with 100 µm thickness. After the temperature gradient of 0.33 °C/mm was given for half an hour, the cell was moved at a constant velocity. Then the vicinity of ice growing surface was observed until the cell was moved by 5 mm distance. The condition on the freezing velocity, V_f, and the particles diameter are shown in Table 2.

Table 2 Experimental conditions for isolated particles system

Particle diameter (Ø, µm)	Freezing velocity (V_f, µm/s)
9.7	4.0, 3.0, 2.0, 1.5
5.3	5.0, 4.0, 3.0, 2.5, 2.0
2.2	5.0, 4.5, 4.0, 3.5, 3.0, 2.5, 2.0

RESULTS AND DISCUSSION

Packed Particles System

Figure 2 shows an image of ice lenses under the temperature gradient of 0.33 °C/mm for V_s =0. Black and white portions are ice lenses and glass beads, respectively. The ice lenses stratified in the direction of heat flow (from right to left in figure). An ice lens was thicker as it was formed later. The warmest ice lens grew to 3.5 mm-thick for 10 hours. Such ice lensing was observed in other experiments under different temperature gradients for V_s =0.

These observations show that frost heave may occur in glass beads as well as in soil. The freezing experiment for V_s =0 corresponds to frost penetration in nature in which freezing velocity decreases gradually and the thickest ice lens is found near the final 0°C isotherm.

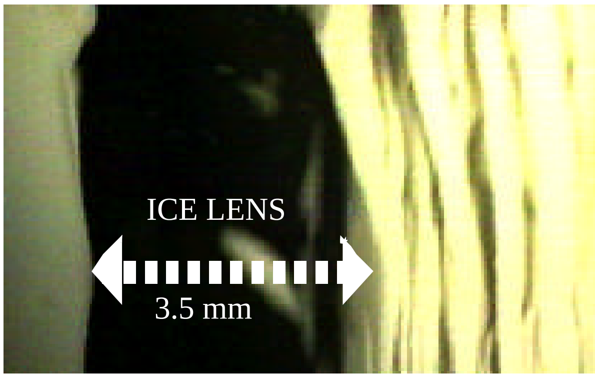

Figure 2. Final ice lens formed in the packed particles system under A = 0.33 (°C/mm),Vf = 0 (µm/sec) and Ø = 2.2 (µm) Ice lens are black and glass beads are white. Final ice lens is the thickest ice lens. Right: cold, Left: warm.

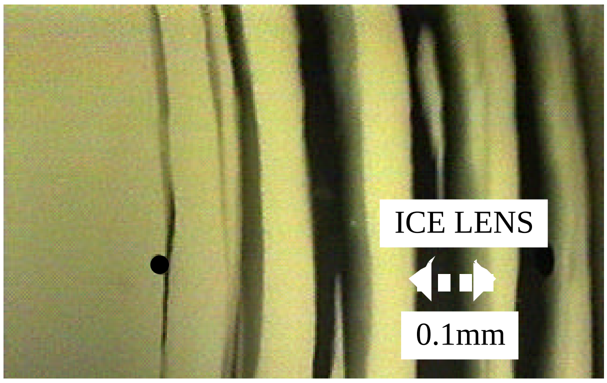

Figure 3. Ice lenses formed in the packed particles system under A= 0.20, Vf = 0.8 and Ø = 2.2.
Ice lenses are black and glass beads are white. Right: cold, Left: warm. An ice lens starts to grow at the location of solid circle.

Therefore, observing artificial ice lensing in the glass beads will be useful in understanding of frost heave.

Figure 3 shows ice lenses under the temperature gradient of 0.20 °C/mm for V_s = 0.8 µm/sec. Stratified ice lensing with same thickness and same space grew from cold to warm sides (from right to left in figure). Each ice lens started to grow at the same location (at the same temperature) in the visual field of microscope. The warmer end of the ice lens moved toward cold side with growing ice lens, i.e. pushing glass beads ahead at the colder end of the ice lens. This indicates that the growth rate of an ice lens was slower than V_f and that the temperature at the warmer end of the

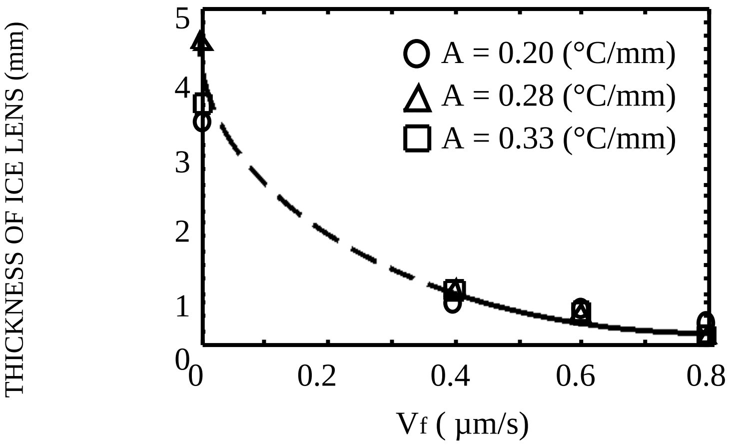

Figure 4. Relationship between freezing velocity and thickness of ice lens.
Thickness of ice lens depends on freezing velocity.

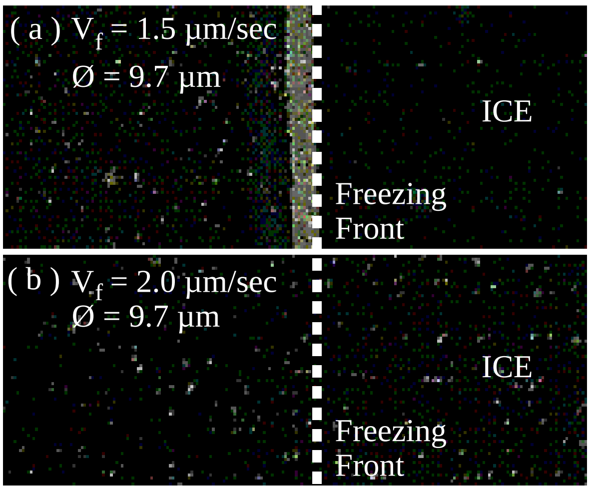

Figure 5. Exclusion (a) and encapsulation (b) of isolated particles
The right of a dashed line is frozen and the left is unfrozen. White particles are glass beads.
(a) Ice grows with pushing isolated particles ahead:
(b) Ice grows with encapsulating isolated particles.

growing ice lens was lower than the temperature at which the ice lens starts to grow. When the warmer end of the growing ice lens moved by a distance from the location at which the ice lens started to grow, the ice lens stopped growing and a new ice lens started to grow at the previous location. This behavior can be regarded as frost heave under a constant freezing velocity. Figure 4 shows relationship between thickness of ice lens and freezing velocity. The thickness of ice lens decreased as the freezing velocity increased.

Isolated Particles System

Figure 5 shows exclusion and encapsulation of isolated particles. Two kinds of ice formations were observed in the isolated system. The right side of a dashed line shown is frozen area and the left is unfrozen. Ice grew with pushing particles ahead at a low freezing velocity (Figure 5a) while it grew with encapsulating particles at a high freezing velocity (Figure 5b). In this experiment, the ice growing surface stayed at the same location in the visual field of microscope. The behavior of ice surface shows that the ice growth rate was equal to the freezing velocity and that the ice growing surface kept the same temperature.

Table 2 shows freezing velocities for three kinds of glass beads to examine criteria whether particles were encapsulated in ice or not. Underlines denotes the freezing velocity that particles were pushed ahead by ice. For 9.7 μm-diameter glass beads, ice encapsulated particles at the freezing velocities of 4.0, 3.0 and 2.0 μm/sec while ice grew with pushing particles ahead at the velocity of 1.5 μm/sec. The critical velocity, V_c, was affected by the particle size.

Körber et al. (1992) has shown the criterion for such a particle trapping phenomena. According to their theory, an isolated particle pushed to an advancing ice front is subject to two counteracting forces: an attractive and a repulsive force. The attractive force comes from viscous drag due to fluid flow around the particle which favors entrapment, and the repulsive force originates from van der Waals forces. The balance of the two forces determines whether the particle is encapsulated or not.

Our experimental results in the isolated system can be explained by Körber's theory. However, since this theory deals with the forces around only one particle, it dose not explain the stratified ice lens observed in the packed particles system. In fact, we often found that a new ice started to grow beyond the particles layer shown in Figure 5a after the particles had accumulated to a certain thickness. Although details of the phenomenon were not examined, the new ice growth in the isolated particles system must be related to the ice lensing in the packed particles system. Nevertheless, it is obvious from our experiment in the isolated system that both particle size and the freezing velocity are important factors for ice lensing in the packed glass beads.

CONCLUSION

We observed microscopic ice lensing in glass beads by using an apparatus which can control temperature gradient and freezing velocity independently. As a result, we found that artificial ice lenses were formed in the glass beads and that thickness of the ice lenses depended on freezing velocity. In addition, we observed the criteria for exclusion and encapsulation of glass beads particles during ice formation with respect to particle size and freezing velocity. The result suggests that particle size and freezing velocity are important factors for ice lensing. In conclusion, microscopic observation of artificial ice lensing in the glass beads will be helpful in understanding the mechanism of frost heave.

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