Ice Lensing Mechanism during Soil Freezing

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ABSTRACT

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When soil is cooled under 0 ˚C, soil water solidifies with decreasing temperature. This is known as soil freezing. In Japan, the ground is frozen seasonally in Hokkaido, Tohoku, and some mountain areas. Short-term frozen ground is even found in the western part of Japan. Soil freezing is estimated to occur in almost 70 per cent of the Earth's land surface. Furthermore, soil is sometimes frozen artificially for use. There are many situations in which soil freezes.

If soil expands when it freezes, the volume change is called frost heave. When heaving occurs, some of the ice layer formed near the ground surface is present as seems of pure segregated ice; this ice layer is called an ice lens. The ground surface sometimes expands dozens of centimeters due to the ice lensing. It causes much damage to paved road, drainage system in farmland, foundation, and so on. The growth of ice lenses induces soil water to flow from the unfrozen zone to the surface zone. In this case, some solutes illuviate to near the ground surface with the water flow. To overcome such frost-action damage, it is important to clarify the mechanism of ice lensing during soil freezing. Furthermore, ice lensing is not a phenomenon limited to soil. It has also been observed in various porous materials. Knowledge of the mechanism of ice lensing will be applied to fields that involve these frozen materials, including physical chemistry, biology, material science, food processing, and medicine.

Numerous studies with the intention of clarifying the mechanism of ice lensing have been reported. Presently, one of the theories most often used is the secondary frost heave theory. In this theory, presence of partially frozen region near growing surface of ice lens is assumed. The intermittent formation of ice lenses is then explained from calculating stresses in the region. However, the partially frozen region has not been confirmed experimentally. And the stress partition factor, which is important for calculating the neutral stress, has not been theoretically verified. Summarizing the historical studies, there are two problems associated with clarifying

mechanism of ice lensing. One is to clarify the microstructure near the freezing front, i.e. to clarify water conditions and particle migration in the partially frozen region. The other is to explain the dynamic mechanism of ice lensing, in which the generation and growth of an ice lens is repeated to form intermittent layers. In order to solve these problems, we performed three series of freezing experiment using a unidirectional freezing apparatus. In the first experiment, ice lensing in soil and porous media consisting of fine particles were microscopically observed, then, following results were obtained. Ideal ice lenses for modeling can be made using uniform sized glass beads. The growth of ice lens is dependent on supercooling of the growth surface. The freezing rate influences the ice lens growth more than temperature gradient. It is suggested that freezing rate, supercooling degree at growth surface of ice lens and particle condition near growing ice lens were important factors for considering ice lensing model. From the second experiment, in which ice interface in water with dispersed glass particles was observed, the criteria for exclusion and encapsulation of particles during ice formation with respect to particle size and freezing rate was shown. The relationship between particle size and critical freezing rate was explained by Köber's theory. It is suggested that the critical freezing rate was important for the generation of ice lens. In the third experiment, microstructure in the vicinity of ice lens is observed using Raman spectroscopy. It is obtained that no ice was found in any pore warmer than the warmest ice lens in the porous media and the ice lens grew without penetrating the warmer pores.

Based on the experimental results, we then presented a model for simulating the formation of ice lenses during freezing of unconfined uniform porous media is presented. The main notions of the model are that generation and jump are dependent on the freezing rate, and growth is dependent on supercooling. The critical freezing rate is assumed to vary with changes in the number of particles near the ice lens as it grows. The model was demonstrated for the unidirectional freezing of a porous medium consisting of fine glass particles. The numerical results show that this model can represent the formation of intermittent layers of ice lenses in such a system. This model can be applied to ice formation in unconfined water-soaked porous media.

As mentioned above, we clarified the microstructure near the freezing front in water-saturated porous media experimentally and made a model, which can explain the formation of intermittent layers of ice lenses.

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LIST OF SYMBOLS

symbol	unit	meaning
A	m^2	area
	$m^{-2}s^{-1}$	coefficient
a_0	m	average molecular distance in liquid
B	$m\ s^{-1}K^{-1}$	coefficient
C	$mol\ kg^{-1}$	molality
	$J\ K^{-1}kg^{-1}$	specific heat
	m^{-5}	coefficient
D	$m^{-2}s^{-1}$	self diffusion coefficient of water molecule
d	m	distance
	m	mean particle diameter
E	J	internal energy
F_η	N	viscous drag force
F_γ	N	repulsive force
G	J	Gibbs free energy
g	$m\ s^{-2}$	gravitational acceleration
H	J	enthalpy
J	$s^{-1}m^{-2}$	flux of water molecule
K	$m\ s^{-1}$	hydraulic conductivity
K_f	$K\ kg\ mol^{-1}$	molar freezing point constant
k	$W\ m^{-1}K^{-1}$	thermal conductivity
k	$J\ K^{-1}$	Boltzman coefficient
L	$J\ kg^{-1}$	latent heat of fusion
m	kg	mass
N	m^{-3}	number of particles per unit volume
p	Pa	pressure
Q	W	heat flux
R	m	radius of particle
R_f	$J\ m^{-1}s^{-1}$	resistance from freezing process
R_h	$J\ m^{-1}s^{-1}$	resistance from water flow
r	m	curvature radius
r_p	m	radius of pore
S	$J\ K^{-1}$	entropy
SP	$m^2K^{-1}s^{-1}$	segregation potential
T	K, ˚C	temperature
t, t_p	s	time
T_m	K, ˚C	melting temperature of bulk water
U_c	-	coefficient of uniformity
U_c’	-	coefficient of curvature
V_c , V_c’	$m\ s^{-1}$	critical rate of progress of freezing front
V_f	$m\ s^{-1}$	rate of advancing of freezing front

LIST OF SYMBOLS

symbol	unit	meaning
V_h	m s^{-1}	heaving rate
V_{il}	m s^{-1}	rate of ice lens growth
V_s	m s^{-1}	rate of moving of sample cell = - V_f v m^3 specific volume
x	m	coordinate
z	m	coordinate
α	K m^{-1}	temperature gradient
β	-	constant
χ	-	stress partition factor
ΔT_f ,ΔT	K, ˚C	temperature difference from T_m
$\Delta\mu$	J	chemical potential
γ	J m^{-2}	interfacial energy
η	N s m^{-2}	coefficient of viscosity
ι	-	van't Hoff coefficient
ν	m^{-1}	number of vibration
ν_R	m^{-1}	Raman shift
Π	Pa	osmotic pressure
ρ	kg m^3	density
σ	Pa	stress

subscript	meaning
e	effective
f	frozen, freezing
H	high
h	heave
i	ice
il	ice lens
L	low
l	liquid
n	neutral
p	pore
q	quasi-liquid
s	solid, soil, sample
u	unfrozen
w	water