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Unfrozen Water Content of Artificially Frozen Soil

By Yoshiaki FUKUO and Yoshio ARIGA

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Abstract

This paper describes the measurement of unfrozen water content (expressed as a percentage of the dry weight) of soil samples frozen artificially in the laboratory with a specially designed calorimeter. The sample was cooled at specified temperatures over a definite time in the brine cooling vessel.

In this measurement, the range of freezing temperature and the periods of freezing were taken for −4 to −28°C and 20, 40, 91 hours respectively.

The results of the measurement show that the amount of unfrozen water decreases of course with the length of the freezing period but, against expectation, that it increases with the lowering of the specified cooling temperature over 20 hours of freezing.

1. Introduction

The study of unfrozen water is significant for clarifying the mechanism of water movement accompanied by frost heaving.

It is well known that when soil containing water freezes, it expands much more than one would expect from expansion due to the freezing of the water that is in the soil (Beskow, 1947). This shows that the water must be available for a large amount of frost heaving and that water movement from the water table exists.

The freezing temperature of water in soil is related mainly to the state of stress (PF) produced in the soil water by several effects. Water in soil under the adsorption force produced by the soil particles will have a very low freezing point and can not be frozen easily (A. B. C. Anderson and N. E. Edlefsen, 1942). This unfrozen water film plays the part of the waterway through which the water moves.

From this point of view, it is desirable to investigate exactly and fully the property of unfrozen water in frozen soil.

P. J. Williams measured the unfrozen water content of frozen soil in the range of freezing temperature 0°C to −5°C and reported the relationship that the amount of unfrozen water decreased logarithmically as the freezing temperature was lowered (P. J. Williams, 1964).

His result is difficult to compare because of different freezing situations and it has not yet been measured by anyone below the temperature of −5°C.

2. Soil samples

A block of earth soil was sampled from the alluvial layer in Tokyo. The soil mechanical properties and particle size distribution of this block are shown in Table 1 and Fig. 1 respectively.

TABLE 1.
Physical properties of undisturbed soil sample.

Properties of soil sample	Values
Bulk specific gravity	1.92 gr/cm^3
Specific gravity of soil particle	2.69 gr/cm^3
Water content in weight	30.6 %
Particle content in volume	55 %
Water content in volume	45 %
Air content in volume	0 %
Liquid limit	40.4 %
Plastic limit	21.8 %

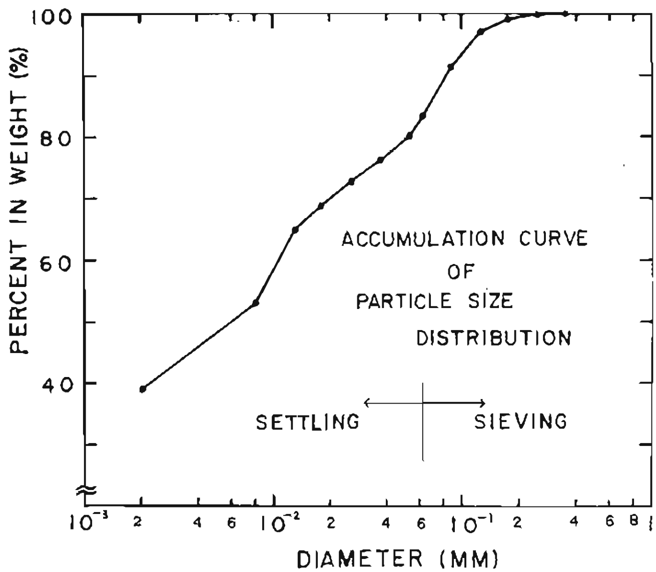

Fig. 1. Accumulation curve of particle size distribution. Diameters were determined by sieving mesh for diameter larger than 62μ and by settling velocity for diameter smaller than 62μ.

The block was divided into several pieces with a wire saw. Each piece was moulded with a trimmer into cylindrical form 3 cm in diameter and 10 cm in height. A moulded piece was put in a case which had a cylindrical hole of the same size and was immersed in a tank of brine cooled by a refrigerator. This frozen piece was used for the measurement of the unfrozen water content.

3. The determination of unfrozen water content present in frozen soils

The amount of unfrozen water was measured by the calorimetric method. A calorimeter consists of a Dewar bottle and thermister thermometer, as shown in Fig. 2. A Dewar bottle surrounded by adiabatic material was used to prevent the outward escape of heat.

At first, 600 cc of warm water was poured into the bottle. Then the frozen soil sample was put into the bottle as quickly as possible and was frequently shaken. The temperature was reached in equilibrium in about 5 minutes. The temperature variation during this procedure was recorded automatically by the thermister thermometer with an accuracy of $\pm 0.1°C$.

After these measurements the muddy water was dried at 110°C by the electric drying oven for two days. The weight of dry soil was measured and its specific heat was also measured using the calorimeter. Ex perimental instruments are shown in Photo. 1.

The calculations determining the amount of unfrozen water of frozen soil sample can be expressed as follows:

$$U = M - M_1 - \frac{Q}{80} = M - M_1 - \frac{(M_3+m)(t_1-t_2) - \{M+M_1(C_1-1)\}(|t_0|+t_2)}{80+(C_2-1)|t_0|}$$

U: The amount of unfrozen water of the sample
M : Weight of soil sample
M_1: Weight of dry soil sample
M_2: Amount of ice of frozen soil sample
M_3: Weight of warm water
m : Water equivalent of the bottle

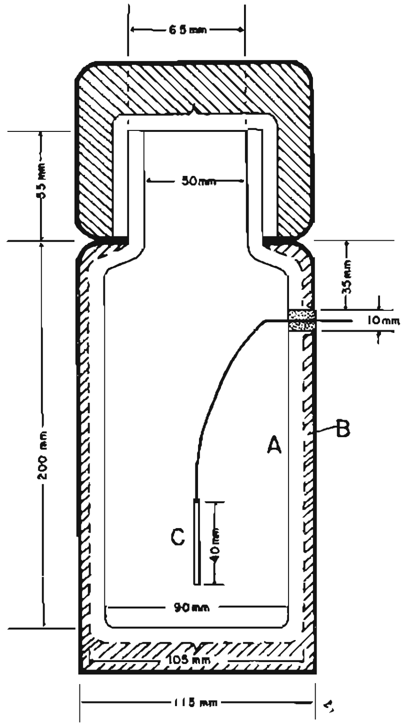

Fig. 2. The calorimeter (A) Dewar bottle, (B) adiabatic material, (C) thermister thermometer.

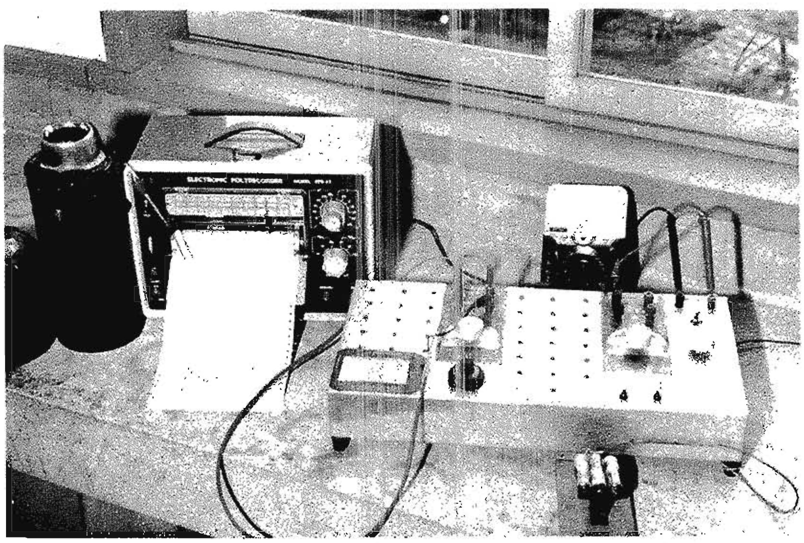

Photo 1. Experimental instruments (calorimeter, auto-recorder, bridge circuit).

Q : Heat quantity which the ice of frozen soil deprives warm water of to melt
C_1 : Specific heat of dry soil sample
C_2 : Specific heat of ice at $-10°C$ (0.48 cal/g°C)
t_0 : Temperature of frozen soil sample
t_1 : Initial temperature of warm water
t_2 : Equilibrium temperature after the frozen soil sample was put into the bottle.

4. Results and some considerations

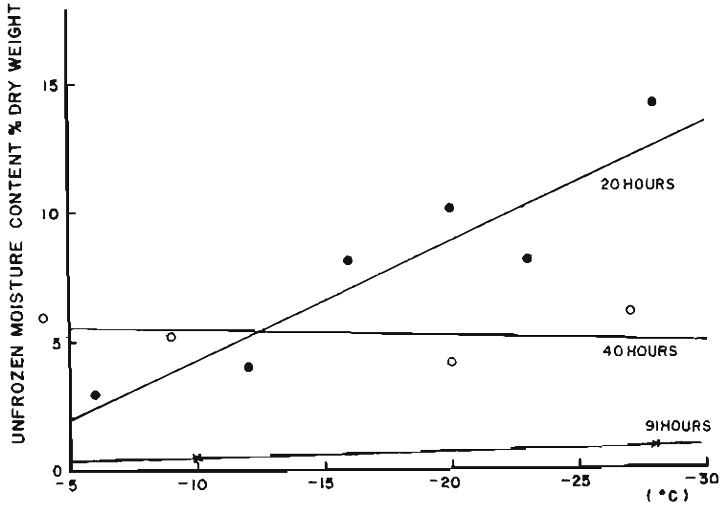

Fig. 3. Relationship between brine temperature and unfrozen moisture content over the freezing periods of 20, 40 and 91 hours.

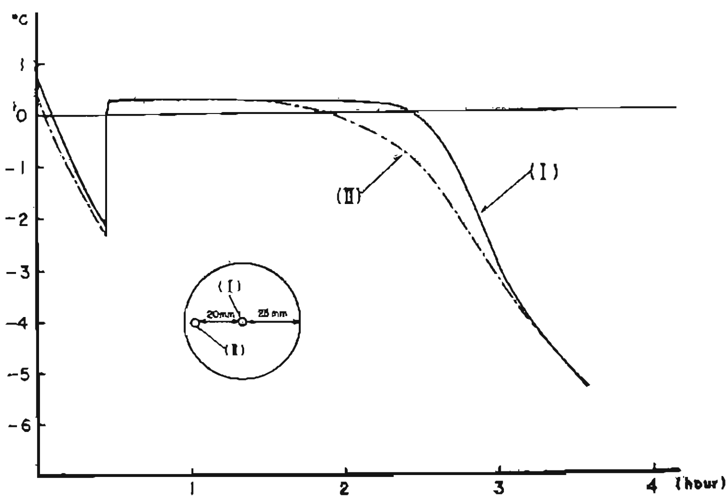

Fig. 4. Cooling curve of soil sample to compare the cooling rate between the center (I) and the outside (II) at the brine temperature of $-10°C$.

Some results are shown in Fig. 3, from which it is seen that the unfrozen water content of frozen soil depends on both the freezing temperature and the freezing time.

An interesting phenomenon is that the unfrozen water content increases with a lower cooling temperature over a freezing period of 20 hours and decreases with a longer freezing period.

It may be suggested that by rapid freezing the inclusion of the soil particles in the ice is brought about, at the same time the pressure to be applied to soil particles increases and then it gradually declines with time.

The cooling curve of the soil sample is shown in Fig. 4. The cooling rate in these experiments was from 0.15 to 0.30°C/min, which was calculated at the supercooling region from the cooling curve. Experiments have been planned to examine the above relationships in detail using ideal soil samples.

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