Introduction

The formation of microstructures in frozen soil and the laws governing changes in microstructure are key subjects in geocryology. The microstructures in frozen soil not only affect the physical and mechanical properties, but also can reveal the failure mechanism of frozen soil under the action of bearing forces. Additionally, many periglacial phenomena in permafrost regions, such as patterned ground, ice wedges, frost mounds and other features, are related to changes in the microstructure of soils during freeze-thaw cycles under natural conditions. Research in this area has been moving from geomorphic to physical-mechanical and physical-chemical approaches (Ershov et al., 1988).

The microstructure changes in soils during the freeze-thaw cycles are due to water migration and phase transitions. The influencing factors of soil types, salt type and concentration, water content and water supply, temperature, and bearing forces on the formation of microstructures in freezing soils were investigated in the laboratory using optical and electronic scanning microscopes. A combination of the five factors mentioned above creates the different patterns of water migration and ice formation. The purpose of this paper is to present the test results and analyses of the influence of these factors.

Influence of soil, salt, water, temperature and overburden pressure on the formation of microstructure

INFLUENCE OF SOIL TYPES

The following results were obtained after 72 hours of controlled-freezing tests on five types of soils under the same temperature boundary conditions. Figure 1 shows the structures of different types of frozen soils. An ice layer 7.2 cm thick was formed in Japanese volcanic ash...
The influence of salt composition and salt concentration

With increasing salinity, the freezing point of the unfrozen solution decreases and the unfrozen water content increases and the degree of ice segregation decreases. Figures 3, 4, and 5 show the microstructure of the Lanzhou silt with three types of solutes at different concentrations. From Figure 3 it can be seen that micro-layered ice strips are formed in the Lanzhou silt with sodium chloride and that these become thinner with increasing concentration. From Figure 4 and 5 it can be seen that, when sodium carbonate or sodium sulphate concentration is equal to 0.5 mol/l, only a micro-layered structure is observed, regardless of the soil. With increasing concentration, the structure changes from micro-layered ice strips to a network structure. This phenomenon is more obvious in the soil with sodium carbonate than that with sodium sulphate. The network structure may form because the solubility of sodium carbonate and sodium sulphate decreases with decreasing temperature and soda crystals and mirabilite crystals create cracks in the soils as they grow when the soil is dried. Ice then forms in the cracks.

Table 1. Physical properties of Inner Mongolia clay and Lanzhou silt

<table>
<thead>
<tr>
<th>Soil</th>
<th>Particle size composition (%)</th>
<th>Pore volume</th>
<th>Average pore diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1-0.05</td>
<td>0.05-0.005</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Inner Mon. clay</td>
<td>2.5</td>
<td>48.1</td>
<td>49.4</td>
</tr>
<tr>
<td>Lanzhou silt</td>
<td>5.4</td>
<td>78.7</td>
<td>15.9</td>
</tr>
</tbody>
</table>

Table 2. Values of latent heat and hydraulic conductivity of the frozen soils

<table>
<thead>
<tr>
<th>Soil</th>
<th>Japanese ash</th>
<th>Linxia kaolinite</th>
<th>Lanzhou silt</th>
<th>Inner Mongolia clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent heat (kJ/kg)</td>
<td>193.1</td>
<td>134.23</td>
<td>104.08</td>
<td>89.68</td>
</tr>
<tr>
<td>Hydraulic conductivity (10⁻⁶ cm/s)</td>
<td>32.17</td>
<td>18.7</td>
<td>6.49</td>
<td>6.96</td>
</tr>
</tbody>
</table>
Under the same temperature conditions, the solubility of sodium sulphate is lower than that of sodium carbonate, thus the network structure is more developed in silt with sodium sulphate than that with sodium carbonate. The solubility of sodium chloride is higher, no salt crystals were formed under the testing temperatures and no network structure was observed.

**INFLUENCE OF WATER SUPPLY**

Figure 6 shows the test results for open and closed systems under the same conditions of initial water content, dry density and temperature. It can be seen that the number and the thicknesses of the ice lenses are much greater in the open system test than those in the closed system. This indicates that the water supply was ample in the former for water migration and ice segregation during the soil freezing process.

**INFLUENCE OF COOLING RATE**

Figure 7 shows the microstructures formed under different cooling rates. It can be seen that a limit exists for developing microstructures as temperatures at the cold end of the silt column decrease linearly. At first, the water intake flow increases and the segregated-ice layers become thicker and denser with an increasing freezing rate and increasing temperature gradient. After the cooling rate reaches a certain value, the water migration becomes insufficient and the segregated-ice layers become thinner and less numerous because the freezing penetration rate is too fast.

**INFLUENCE OF BEARING FORCES**

The bearing force influences the direction of water migration, its flux and the temperature of the phase transition, thus changing the microstructure of soils during freezing. Results indicate that the microstructure of frozen soils changes from a layered to a massive structure with increasing overburden pressure. Only the massive structure could be seen when the overburden pressure reaches 2 MPa because the direction of the acting force opposes the direction of water migration and lowers the freezing point. When the injection-water force direction is the same as the direction of water migration, the development of microstructure is accelerated (Wang et al., 1995b).

**Changing laws of microstructure of frozen soils under different patterns of bearing forces**

Experimental results show that during creep in frozen Lanzhou silt under uniaxial compression, the key pattern is the formation of micro-cracks. The characteristics of crack formation depend on the stress and loading time. In the case of creep with higher stress and shorter times, the frozen soil is in a brittle condition, with thicker and longer microcracks and secondary cracks spreading with different patterns (Figures 8A and B). In the case of creep with lower stress and longer times, the frozen soil is in a viscous and plastic condition, the microcracks are underdeveloped and are only in the preliminary spreading stage (Figure 8C). In the case of long-term creep at a higher temperature (-2°C), the characteristics of the microstructure are: substance dissociation, ice segregation, compression and coagulation of soil particles and a reunion of colloidal particles (Figure 8D) (Zhang et al., 1994).

Figure 9 shows the microstructure of ice, containing 5 to 10 % of fine sand, under uniaxial compression creep.

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It can be clearly seen that cloud-like features develop when the ice is subjected to compression under low stress. Cracks appear at places of weakened connections between the ice and soil particles because the strength of ice crystals is much lower than that of the soil particles.

Figure 10 shows the microstructure of frozen sand under confining pressure at a temperature of -5°C. It can be seen that the dislocation of soil particles appears first under the action of confined pressure, and increases with increasing pressure. Then, compression wrinkles appear due to extrusion of cementing pore ice surrounding the soil particles. Finally, microcracks are formed, even under low strain ratios (Ma et al., 1995).

Figure 11 shows the microstructures at the broken face of frozen Lanzhou silt during creep and tensile processes. It can be seen that the microstructure also changes greatly.

**Conclusions**

1. Five factors (soil type, salt type and concentration, water content, temperature and pressure) influence ice formation, by changing the degree of water migration and phase transition during soil freezing, to form the different microstructures of frozen soils, such as massive, thin-layered, thick-layered and network structures.

2. Bearing forces between components change the microstructures in the patterns of formation of aggregates, dislocation, brokenness, and pressure melting of ice crystal and folding during soil freezing.

3. The destruction of frozen soil develops in three stages under the action of different forces, i.e., particle dislocation, folding and microfracture.

**References**


