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MASS TRANSFER AND STRUCTURE FORMATION IN FREEZING SALINE SOILS

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Abstract

The correlation between salt and moisture transfer in freezing saline soils was examined experimentally. Salt transfer in saturated soils is primarily due to the transfer of salt ions within migrating water. Depending on various factors (for example, dispersion, mineral composition and external pressure) salt transfer can result in a change in the direction of frozen zone motion, formation of an unfrozen zone or this transfer can be entirely absent. The influence of mass transfer processes on the formation of cryogenic textures in freezing soils was also investigated. The ratio of ice content in mineral layers (pore ice) to segregated ice lenses in saline soils is substantially different from that of ordinary soils. The mechanism of ice layer formation in fine-grained soils changes from migration-segregation to orthotropic-compressive.

Introduction

It is known that the presence of water-soluble salts in freezing dispersed soils suppresses the processes of moisture migration (Chamberlain, 1983; Cary, 1987; Ershov et al., 1992). However, in small concentrations, dissolved substances can increase the water flow at the expense of the influence of the unfrozen water content and the thickness of water films. This has been proven theoretically (Anderson and Morgenstern, 1973; Henry, 1988) and is confirmed by experimental data (Ershov et al., 1992).

The ions of salts in freezing dispersed soils can also be redistributed by the freezing process (Hallet, 1978; Kay and Groenvelt, 1983; Hofmann et al., 1990; Baker and Osterkamp, 1988; Qiu et al., 1988; Xiaozu et al., 1991). As a result, alternating zones with high and low salt concentrations can be formed.

Water-soluble salts have a fundamental influence on the processes of ice formation and the formation of a cryogenic structure (Chamberlain, 1983; Konrad, 1990). However, the relationship between mass transfer and the formation of a cryogenic structure in freezing saline soils needs further investigation. Experiments were carried out to clarify this problem.

Methods

The experimental research was carried out on soils recovered from different regions of Russia. The characteristics of the soils are shown in Table 1. In additions, the experiments involved various additives. When preparing the samples, soil powder was mixed with NaCl (or Na_2SO_4) solutions with different concentrations (0.1 - 1.5 N for NaCl and 0.4 N for Na_2SO_4) and consolidated under mechanical pressures of 0.2 – 1.0 MPa. After consolidation, the samples had a uniform distribution of moisture, density and salinity. The consolidated samples were placed in containers of 4x4x12 cm or 5x5x15 cm size and left in a special apparatus for one-sided freezing. This was constructed based on a conventional freezer and included systems for the temperature control of the samples and temperature measurement inside the samples. The samples were frozen in a closed system with constant boundary conditions on opposite sides (-17°C, -12°C or -8°C at the upper boundary; +8°C at the lower boundary) for 1-2 days. The experiment ended when freezing front stabilisation occurred based on the temperature record. Water content and salt content strain during freezing were determined layer by layer in the samples. Cryogenic textures, macro- and microstructure of the samples were studied in replicated samples and in petrographic sections. The temperature gradient, freezing rate, migration flow rate of water and salts were determined from the experimental data.

To study the influence of external pressures on the processes of mass transfer and cryogenic structure formation, the samples were frozen under pressure created by a mechanical press.

A series of experiments involving the freezing of saline non-consolidated soil were also undertaken to study the character of ice segregation and the new formation of new minerals.

Table 1. Characteristics of soils

Soil type	Particle size distribution, %			Plastic limit, Wp,%	Liquid limit, Wl,%	Index of plasticity, I_p, %	Particle density, ρ_s, g/cm^3
	sand	silt	clay				
kaolinite clay	0.5	44.7	54.8	31.0	51.0	20.0	2.64
montmorillonite clay	0.3	46.2	53.5	44.0	144.0	70.0	2.45
polymineral clay	2.6	70.0	27.4	21.8	44.8	23.0	2.74
polymineral loam	4.5	86.7	8.8	21.9	29.9	8.0	2.69
polymineral sand	97.9	2.0	0.1	-	-	-	2.66

Results and discussion

MASS TRANSFER IN FREEZING SALINE SOILS

The mass transfer of water and the ions of water-soluble salts is determined by the particle size distribution, mineral composition, water content, density, etc.. The experimental data obtained show a strong link between the transfer of salts and water transfer. The maximum accumulation of water corresponded to largest accumulation of salts.

When freezing coarse-grained soils (sand), the freezing front expels water and salt ions of within it into the unfrozen zone (Figure 1). The transition from coarse-grained to fine-grained soils causes water and salts to flow in the opposite direction. The transition from loam to clay for the same freezing conditions causes an increased accumulation of water and salt ions in the frozen zone and a reduction of the thickness of the frozen zone (Figure 2).

In clay soils of various mineral compositions (Figure 3) the water and salt transfer intensity decreased from kaolinite to polymineral to montmorillonite (bentonite) clay. In freezing montmorillonite clay, water and salt redistribution was practically nonexistent in relation to heat flow direction. This is because of its low hydraulic conductivity caused by high dispersity and large active surface, and the absence of loosely bound water in the thawed zone.

With an increase in the initial density of samples, the redistribution intensity of water and salts decreases. The prevailing mechanism of mass transfer is the transport of salt ions, with the flow of water migrating to the freezing front. The identical character of curves for water and salts ion distribution in accordance with the height of the sample speaks about this.

Usually, external pressure suppresses migration of water to freezing front (Ershov et al., 1995). When water migration under pressure is absent, the transfer of salts is not observed either. This indicates the prevalence of salt transport by water flow rather than other mechanisms of salt transfer.

An increase in the salinity in a freezing sample causes a reduction in the freezing rate and a decrease in the thickness of the frozen zone. The water flux to the freezing front has an extreme character (Ershov et al., 1992). At small concentrations of salts, when the micella layer around soils particles is the most advanced, the water migration flux can be more than in an unfrozen sample (Figure 4). At higher concentrations of the pore solution, there is a decrease in the water migration flux as a result of compression of the micella layer.

The flux of salts to the freezing front also has extreme character, depending on the initial salinity of the sample. So, in freezing samples, with boundary conditions -17°C - + 8°C (salinity primarily 0.2 N, 0.8 N and 1.5 N by NaCl) the average the water flux density decreased

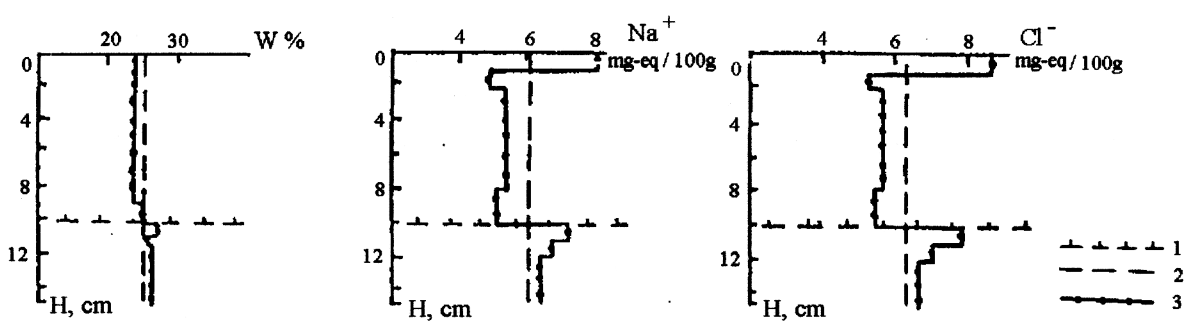

Figure 1. Pattern of the gravimetric moisture content (W) and Na and Cl ions with height (H) of polymineral sand sample freezing at 12°C; 1 - freezing front at the end of the experiment (touches directly on the frozen zone),2 and 3 - initial and final patterns of the gravimetric moisture content (W) and Na and Cl ions, respectively

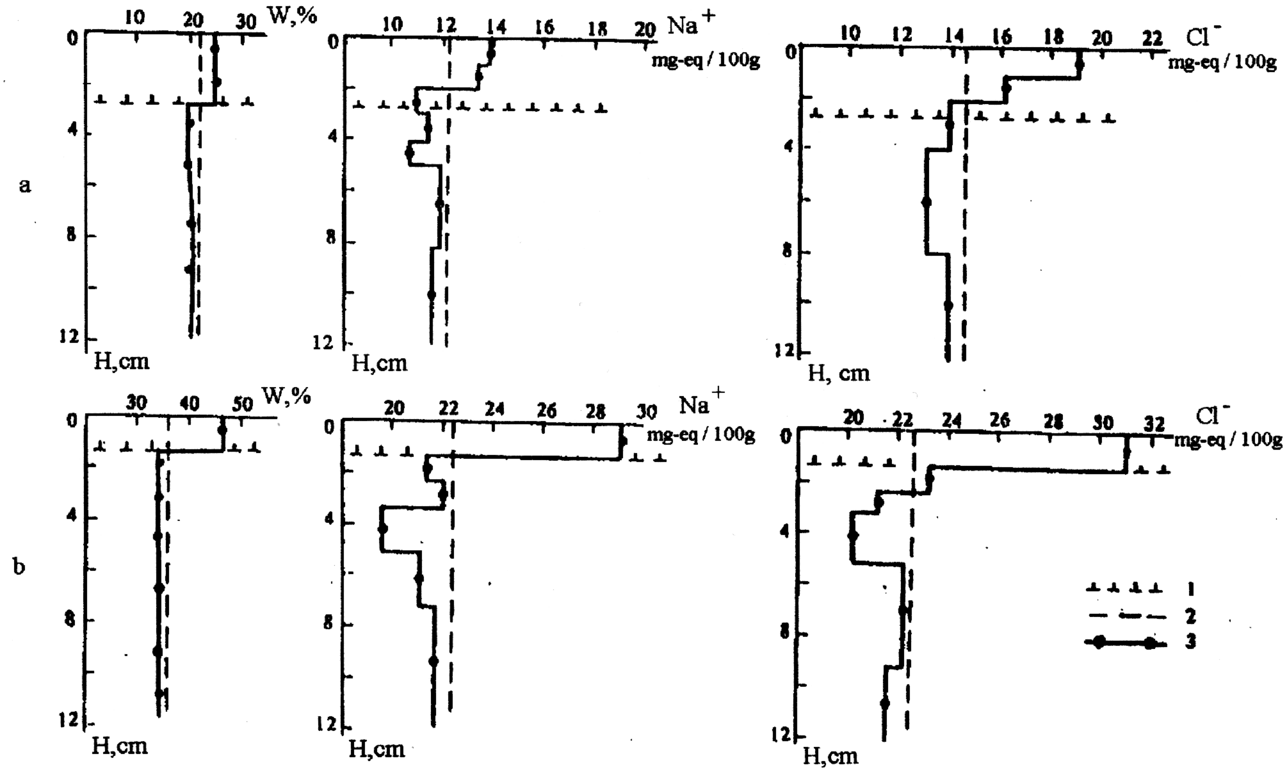

Figure 2. Pattern of the gravimetric moisture content (W) and Na and Cl ions with height (H) of soil samples freezing at -17°C; aloam, b - clay; 1 - freezing front at the end of the experiment (touches directly on the frozen zone), 2 and 3 - initial and final patterns of the gravimetric moisture content (W) and Na and Cl ions, respectively.

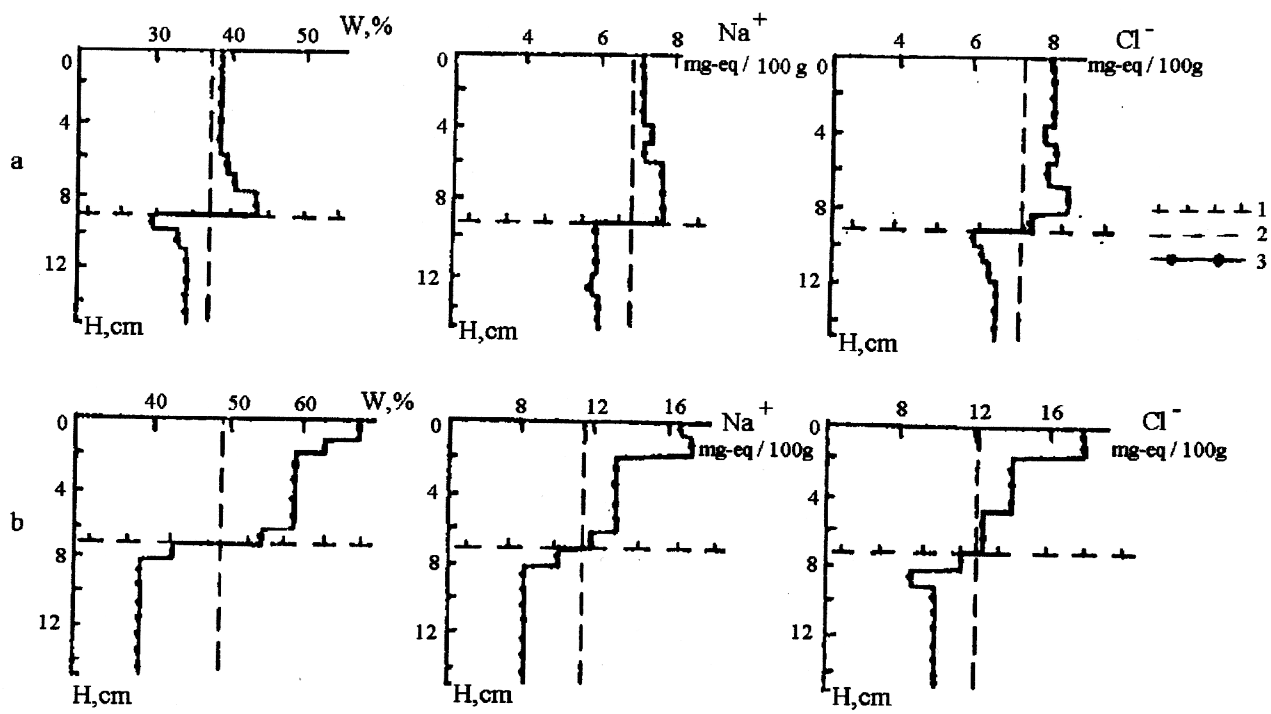

Figure 3. Pattern of the gravimetric moisture content (W) and Na and Cl ions with height (H) of soil samples freezing at -12°C: apolymineral clay, b - kaolinite clay; freezing front at the finishing of experiment (touches directly on the frozen zone), 2 and 3 - initial and final patterns of the weight moisture content (W) and Na and Cl ions, respectively

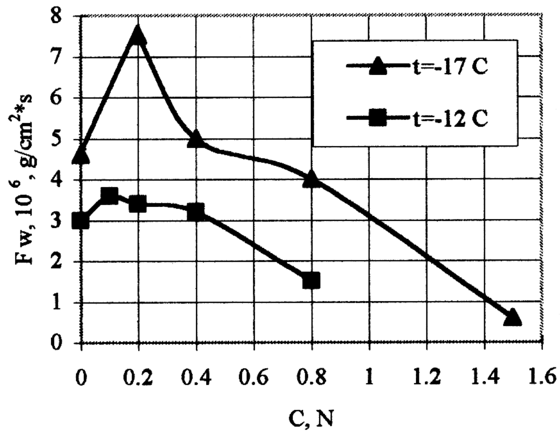

Figure 4. Change of mean moisture flow(Fw) from melted to frozen zone depending on initial salinity (NaCl) of the pore solution (C) in freezing clay (kaolinite).

from: $7.5 \cdot 10^{-6}$ to $3.8 \cdot 10^{-6}$ to $0.5 \cdot 10^{-6}$ g/cm^{2}s. The salt fluxes changed from: $48 \cdot 10^{-9}$ to $117 \cdot 10^{-9}$ to $38 \cdot 10^{-9}$ g/cm^{2}s, respectively. Thus, the decrease of water transfer in a sample with maximum salinity is registered by the minimum redistribution not only of water, but also of salts.

Basic Mechanisms of Salts Transfer in Freezing Soils

Experimental research and analysis of the literature allow the mechanism of mass transfer to be presented as follows. In the uniform mechanism of salt transfer, it is possible for the following to occur: transfer of ions with water migration flux; mechanism of surface conduction caused by the action of adsorption forces; thermodiffusive and diffusive mechanisms for salt transfer under gradients of temperature and concentration (Figure 5). The conducting role in water-soluble salt transfer belongs to the mechanism of water flow.

The identical character of the curves of water and salt ion distribution emphasizes this fact (Figures 1-3). Calculations have shown that up to 80% of salts in water-containing freezing soils are carried by water flow. The rest of the salt transfer is shared among the other three mechanisms.

The uniform mechanism of salt transfer can work in various directions (Figure 5): the mechanisms of surface conduction and the thermodiffusive transfer of water-soluble salts act towards the part with a lowest negative temperature; the mechanism of salts transfer with water flow depends on a direction of water flow movement; the diffusive mechanism is directed towards the total flow of salts. The maximum redistribution of salts ions corresponds to a balance of the intensities of the different salt transfer mechanisms.

The following cases of salt transfer were observed:
- salt accumulation in the frozen part (this is characteristic during freezing of fine-grained soils (loam, clay)) (Figure 5a);
- salt movement to the unfrozen part of the freezing soil (this is characteristic for coarse-grained soils (sand) at standard conditions, and for fine-grained soils at higher external pressures (Figure 5b);

- the absence of water and salt migration in both coarse- and fine-grained soils at very high freezing velocity (Figure 5c).

The Influence of Salinity on the Type of Cryogenic Structure Formed

Experiments show that salinity influences the cryogenic structure of soils with various particle size distributions. In coarse-grained soils (sand), injection of salts does not result in major changes in a cryogenic structure. In fine-grained soils, it results in reduction in the intensity of ice-lens formation. Thus, saline freezing clays form specific cryogenic textures which have an increase in the proportion of vertical lenses relative to horizontal lenses (Figure 6). Overall, salinity has a larger influence on the type of cryotexture formed than the clay mineralogy.

In both saline and non-saline soils, an increase of external pressure during freezing suppresses water migration and results in the formation of a massive cryogenic texture (ice-cement).

Structural changes in freezing saline soils, as opposed to non-saline ones, are dependent not only on the form of ice segregation and transformation, and the initial organic-mineral skeleton, but also on the opportunity for new minerals to form (Rogov and Chuvilin, 1996), the arrangement of which depends on the concentration of the pore solution. For example, at concentrations of the pore solution less then 0.4 N Na_2SO_4 the crystals of mirabilite ($Na_2SO_4 \cdot 10H_2O$) were registered only inside mineral layers of frozen clay. With higher pore solution concentrations, the centres of crystallisation also formed at the contact of the ice-lens with mineral layers and within the ice.

Mechanisms of Ice-formation in Saline Soils

A change in the structure- and texture formation mechanisms during freezing of saline soils takes place under certain conditions. During freezing of non-saline ground, ice-lens formation occurs parallel to the freezing front due to migration of water. Freezing of saline soil suppresses water migration to form vertical ice lenses, according to orthotropic crystallisation of water free of salt ions situated in a field of a mineral substrate. The orthotropic growth of ice-lenses in saline soils looks like ice-crystallisation in silts (Ershov et al., 1996). So there is a change in the mechanisms of ice-lens growth from migration-segregation to orthotropic-compressive.

Quantitative processing of the cryogenic structure image has shown that, after freezing of non-saline

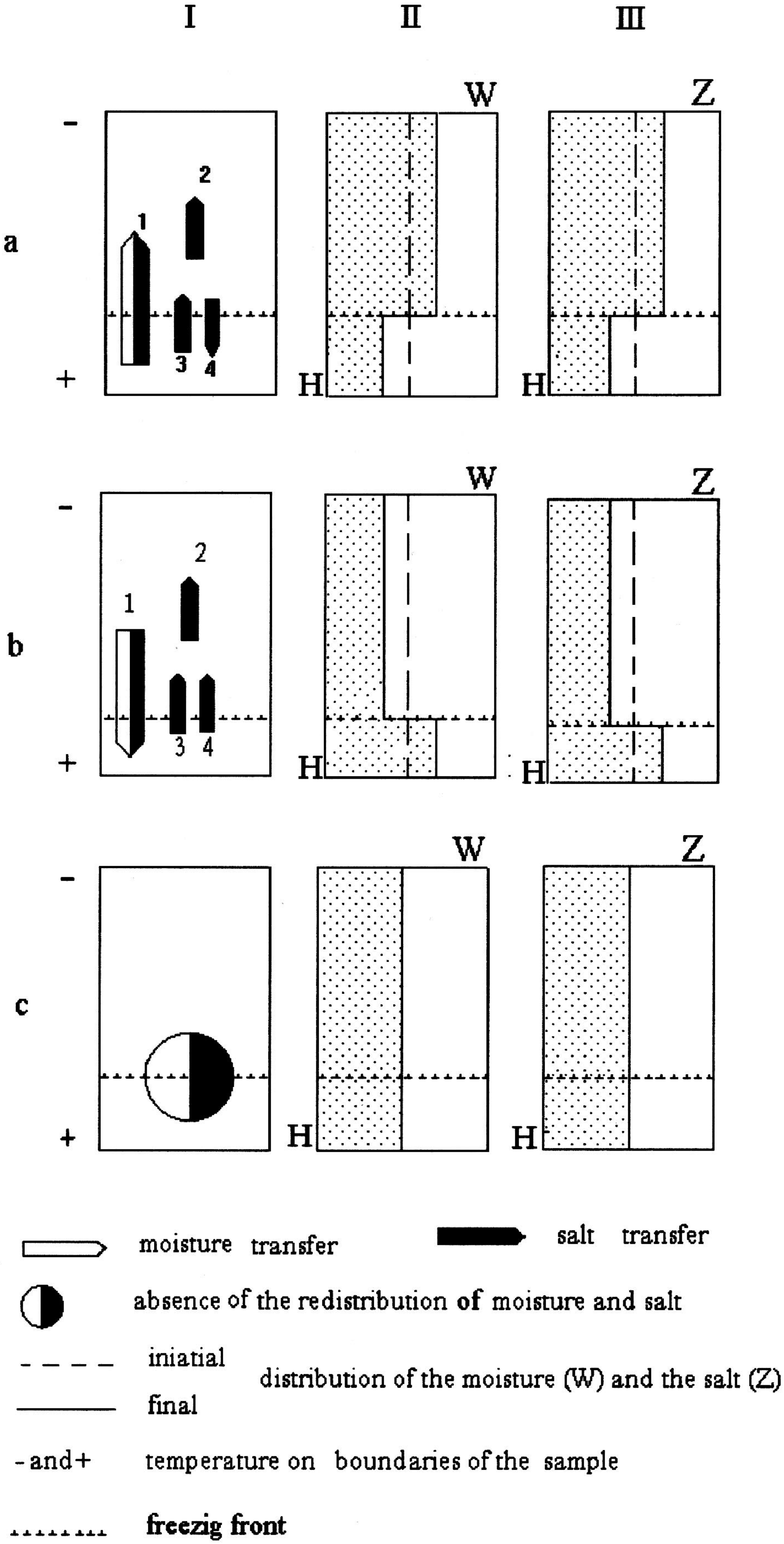

Figure 5. Schematic representation (a,b,c) of processes of (I) mass transfer in freezing saline soils, (I) distribution of the moisture (W), and (III) distribution of the salt (Z) with height (H) of soil samples in the follwing cases: 1,2,3,4 - mechanisms of salt transfer; 1 - transfer ions by migration water flux; 2 - surface (adsorbtion ion transfer; 3 - thermodiffusive; 4 diffusive.

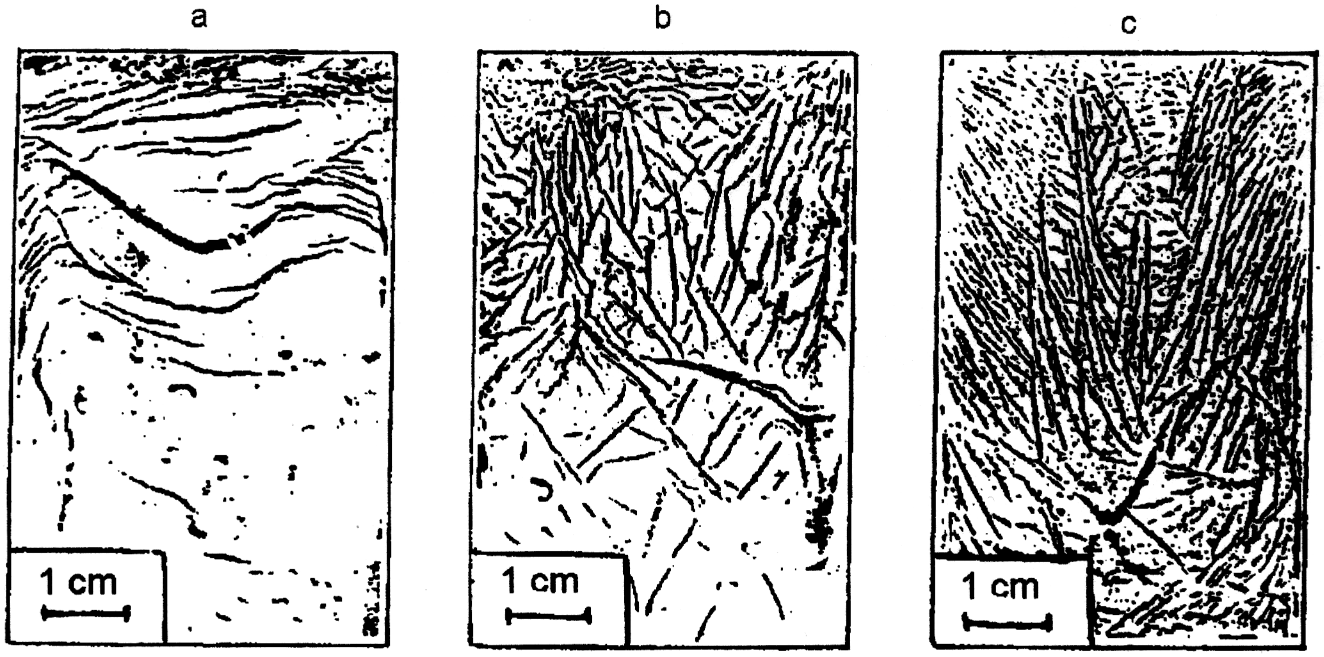

Figure 6. Cryogenic structure of kaolinite clay samples (W=65%) with NaCl solutions of different concentrations: a - c=0.0 N,b - 0.4 N, c - 1.0 N, after freezing at temperature -12°C.

kaolinite clay, the values of ice content in mineral layers and the ice content of the soil created by ice lenses are close. The ice-content in mineral layers in a kaolinite clay containing NaCl (Z=1.2%) at close to the volumetric water content, exceeds the ice of content located in the ice lenses by almost 1.5 times. Thus, in a saline sample, segregation ice lensing decreases as a result of water transfer suppression, and crystallisation of ice occurs more in the form of ice-cement (pore ice).

Conclusion

Analysis of mass transfer processes in freezing saline soils shows, that:

(1) salt movement in freezing soils is a result of ion transfer within the water flux, surface conduction, diffusion and thermodiffusion;

(2) the most important process is the transfer of salt ions within the water flux;

(3) depending on different factors (dispersion, mineral composition, external pressure and others) salt transfer results in a change in frozen zone and unfrozen zone orientations or the transfer can be absent.

The parity of ice content within minerals layers (pore ice) and bulk ice-lenses varies in saline soils: the share of the former increases and the share of the latter decreases with increasing salinity. The mechanism of cryogenic texture formation changes from migration-segregation to orthotropic-compressive with increasing salinity of fine-grained soils.

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