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ICE AND FROZEN GROUND PROPERTIES

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ON THE NATURE OF MECHANOCALORICAL EFFECT IN FROZEN SOILS UNDER UNIAXIAL COMPRESSION

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The paper provides the results of experimental verification of the author's earlier hypothesis about the crack formation playing a major role in the appearance of mechanocalorical effect in the frozen soils, which is underpinned by the data obtained.

Frozen soil, ice, uniaxial compression, mechanocalorical effect, crack formation

INTRODUCTION

This work is a continuation of the previous study of mechanocaloric effect in frozen soils with the results provided in [*Volokhov, 2016*]. The temperature-mechanical properties of frozen soils, along with the mechanocaloric effect, have been addressed to in numerous publications: by *S.E. Grechichshev* [*1976*], *O.V. Kazakova* [*Grechichshev et al., 1984; Kazakova, 1984*], *R.V. Maksimyak* [*1988*], *A.A. Konovalov* [*1999*], *J.B. Gorelik and V.S. Kolunin* [*2002*] whose detailed overview is provided in [*Volokhov, 2016*].

Previously, the author [*Volokhov, 2016*] established that the uniaxial compression-driven mechanocaloric effect in frozen soils, which primarily implies an increase in soil temperature in response to mechanical loads, develops only when either rapid incremental loading is applied, or is caused by the progressing creep during ductile-brittle failure of soils, and is absent at the attenuating creep stage and under viscous degradation of frozen soil samples. The assumption on the relationship between a temperature increase in frozen soils and crack formation has been experimentally proved.

This paper is set out to verify the hypothesis on a key role played by the crack formation process during degradation of frozen soils, prompting thereby the mechanocaloric effect.

RESEARCH METHODS

Kaolinite clay (Chelyabinsk area) was used as the test material. In the experiment, the loading was applied to the samples with undisturbed structure. The values for total moisture content and density of frozen soil samples were 50 % and 1.55–1.56 g/cm^3, respectively. Ice samples prepared from degassed and distilled water subjected to the layer-by-layer freezing in steel cylinders were also tested. The uniaxial compression tests were carried out using advanced version of the KPr-1 testing systems equipped with cooling chambers and special centering devices (Fig. 1) which ensured vertical centering of samples and precise axial stress direction when applying the external loading. Each instrument was furnished with clock-type gauges (manometers) measuring deforma-

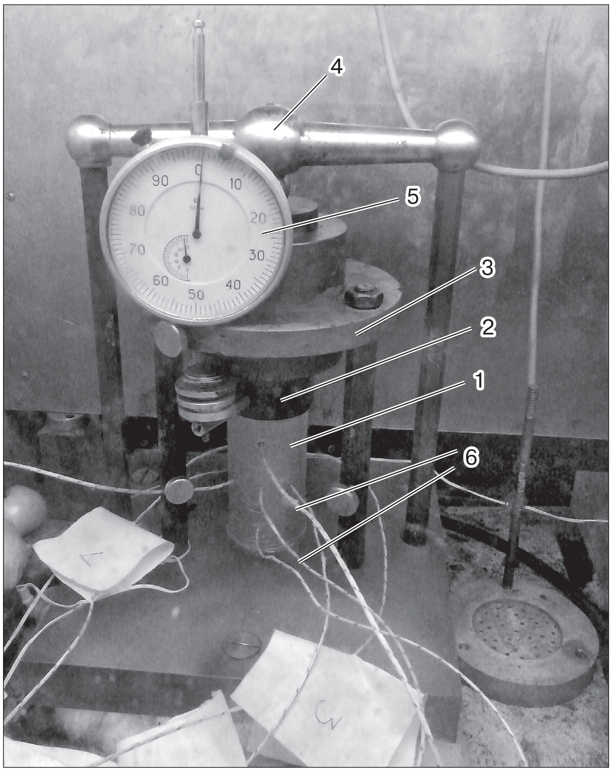

Fig. 1. System for uniaxial compression test.

1 – sample; 2 – mold; 3 – centering device; 4 – loading frame; 5 – indicator; 6 – thermocouples.

tion with an accuracy of 0.01 mm. The testing system allowed to set the temperature in the range from +20 to −20 °C and to maintain it with an accuracy of ±0.1 °C. The temperature was measured in the samples using Testo-176-T4 temperature loggers and seven thermocouples, providing accuracy to 0.1 °C.

The tests were performed on cylindrical samples of frozen soil and ice, each 90 mm in height, 45.15 mm in diameter. The samples were rubber-coated, to prevent their sublimation. In order to insert thermocouples inside the prepared samples, seven 1 mm holes (in dia) were drilled into them (Fig. 2) to various depths.

Three 26 mm deep holes were drilled along the vertical generatrix at the points corresponding to the middle of a third of each sample height (Fig. 2, *a*), allowing placing the central thermocouple in the sample middle. Other four 10 mm deep holes were drilled radially at 90° angle to each other along a circumference in the middle of the sample (Fig. 2, *b*). At the pre-test stage, the sample was placed into the loading system; thermocouples were incorporated into the holes drilled in the sample and connected with temperature loggers. The samples were not insulated and were kept individually at the experiment temperature for at least 24 hours.

Each of the twin samples of frozen clay were systematically loaded in constantly incremented mode (4.25, 4.00, 3.75, 3.50, 3.25 and 3.00 MPa) at −7 °C. Once the load was applied, the deformation was measured every 1 minute. The tests were carried out under creep conditions until the sample failure.

Additionally, the ice samples subjected to rapid incremental and stepwise loading were tested at temperatures −7 and −1 °C. Rapid incremental loading was applied at a rate of 0.125 MPa/s at the both temperatures with the load increasing until ultimate failure of the samples. Whereas stepwise loading of the samples was performed at 0.25 MPa at specified temperatures in steps, the duration of each was 10 min. The tests were carried out until ultimate failure of the samples.

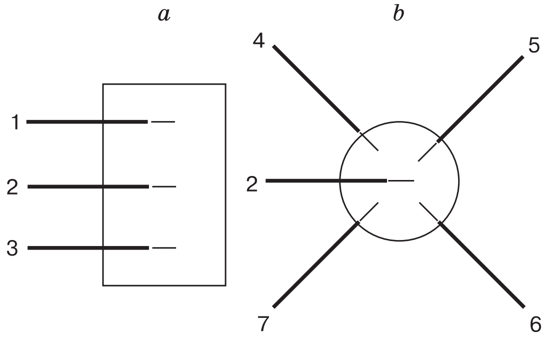

Fig. 2. Layout of thermocouples in the sample:

a – alomg the sample height; *b* – in the sample center; 1–7 – are thermocouple numbers.

The temperature measurements were taken at every 1 s by seven thermocouples incorporated in different parts of the samples (Fig. 2). In order to estimate the initial temperature, its measurement error and variance values over the sample volumes, and the temperature was measured starting 10 minutes before the loading. The measurement error was found to be not exceeding 0.1 °C, while the initial temperature varied over the sample heights and volumes within 0.2 °C. In most of tests the temperature measurements were continued to be taken after samples' failure and unloading.

The resulting creep curves were plotted for samples tested by constant incremental and stepwise increasing loading, as well as time-dependent temperature variation curves for all thermocouples within the samples. In the temperature variation curves provided in this paper, the sample loading started at a time point corresponding to 10 minutes. At this, temperature varied within 0.1 °C (before/during loading and during unloading of the samples), which is consistent with the established measurement error corresponding to the level of "noise".

RESULTS

To test the proposed hypothesis as to whether the role of micro-cracks formation is material in the occurrence of mechanocaloric effect in frozen soils exposed to uniaxial compression, the samples of frozen kaolinite clay were tested at −7 °C under constant incremental loads in the conditions of non-attenuating creep. Had this hypothesis been true, the mechanocaloric effect should have been absent at the stage of attenuating creep (seeing as it develops continuously at a decreasing rate), to occur only at the stage of non-stabilized deformation (increases indefinitely), which implies the failure of sample. The values of constant incremental loading on the samples ranged from 4.25 to 3.00 MPa. The results of the creep test of frozen kaolinite clay samples are presented in Fig. 3, while Fig. 4 shows curves for creep rate change in the samples over time; the temperature curves resulting from these tests are shown in Fig. 5.

The analysis of Fig. 3 and 4 indicates that in all the selected loads, the three creep stages observed were: after *minimum creep rate* was reached, the creep *began to increase*, which was followed by *samples failure*. As the load decreased, so did the creep rate. At the same time, the decreased load had a material impact on the nature of viscous-brittle failure which the samples underwent: the fraction of brittle failure (formation of cracks in the sample) decreased, while the proportion of viscous fracture (change in the sample shape) increased.

From the analysis Fig. 5 it follows that irrespective of the type of loading the sample temperature increased. In case of decreasing load, however, the

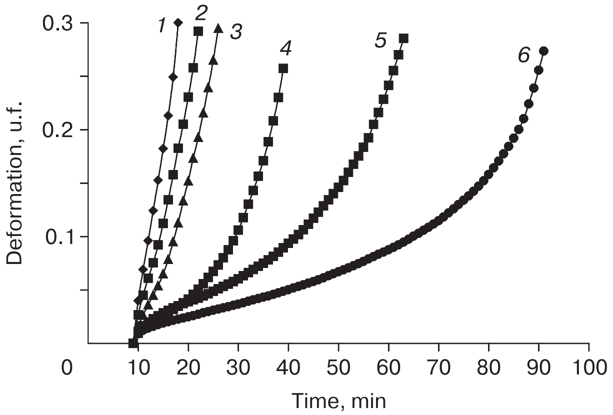

Fig. 3. Creep curves resulting from testing frozen kaolinite clay samples at constant incremental loading:

1 – 4.25 MPa; *2* – 4.00 MPa; *3* – 3.75 MPa; *4* – 3.50 MPa; *5* – 3.25 MPa; *6* – 3.00 MPa.

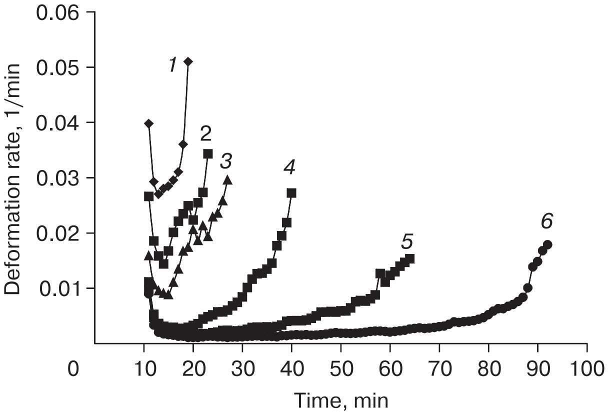

Fig. 4. Variation in creep parameters of frozen kaolinite clay during constant loading:

1 – 4.25 MPa; *2* – 4.00 MPa; *3* – 3.75 MPa; *4* – 3.50 MPa; *5* – 3.25 MPa; *6* – 3.00 MPa.

temperature rise value decreased from 0.4 °C at 4.25 MPa to 0.1 °C at 3.00 MPa.

Table 1 shows the time points corresponding to minimal creep rate (the beginning of sample failure), the onset of temperature rise in the samples, reaching the maximal temperature in the samples, samples failure and unloading calculated from the beginning of sample loading. It follows from the table that the temperature increased in all samples, from beginning of their failure stage, i.e. after the creep rate exceeded the minimum value, giving start to a continuous creep (flow) stage. At the same time, the smaller the

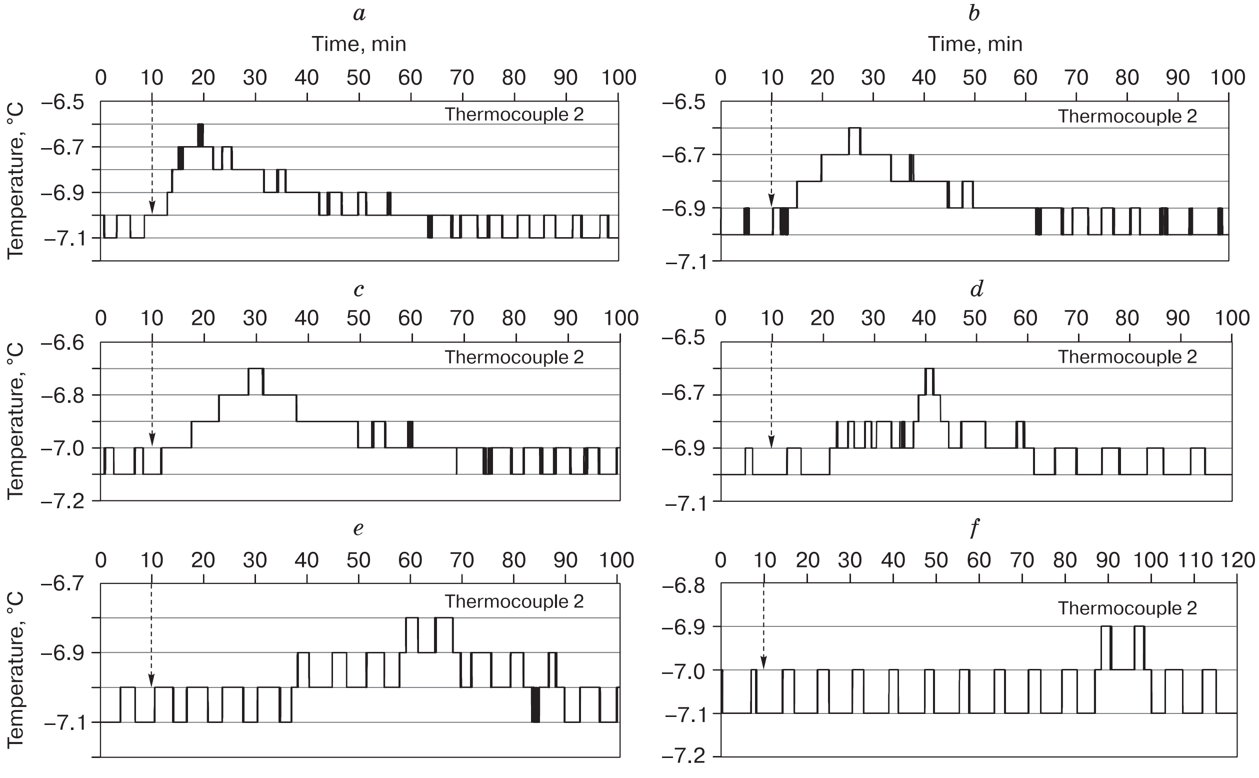

Fig. 5. Temperature variation in the center of samples of clay at rapid incremental loading:

a – 4.25 MPa; *b* – 4.00 MPa; *c* – 3.75 MPa; *d* – 3.50 MPa; *e* – 3.25 MPa; *f* – 3.00 MPa. Initial temperature is −7 °C. Arrow points to onset of loading.

Table 1. **Characteristic points of time (min) during the uniaxial compression test of kaolinite clay samples at –7 °C**

Load applied to sample, MPa	Time of the beginning of sample failure	Time of sample temperature starting to rise	Time of sample temperature reaching maximal value	Time of sample failure and unloading
4.25	3	3.0	8.9	9
4.00	4	5.0	15.2	16
3.75	5	7.6	18.5	19
3.50	8	14.8	29.9	31
3.25	13	28.2	49.2	55
3.00	17	78.4	78.4	82

value of load triggering the sample failure, the further the start of the temperature increase in the samples from the moment the minimum creep rate is reached, which can be associated with the fact that as the loading decreases and, accordingly, the creep rate, the time preceding the formation of cracks increases during the viscous-brittle failure of samples. The temperature rises to the maximum in the samples at the time of sample failure (Table 1).

In case of brittle and viscous-brittle failure of frozen soils, the cracks resulting from mechanical loading pass through the schlieren, grains and other ice inclusions. In this context, ice samples exposed to uniaxial compression were tested at rapid incremental and stepwise loading both at –7 and –1 °C, accompanied by the temperature measurements in the samples.

Given the ice samples were subjected to rapid incremental loading, the values of loads initiating sample failure at –7 and –1 °C, were 3.38 and 2.75 MPa, respectively. Once these values were reached, the brittle failure of the samples was observed. At both temperatures, the ultimate brittle failure (samples shattering through the multitude of cracks) occurred in the upper two-thirds of the samples, while the lower thirds of the samples remained undisturbed.

The variations of ice samples temperature induced by rapid incremental loading at –7 and –1 °C as initial temperatures is shown in Fig. 6. At –7 °C, at the time of the failure in the middle of the upper third of the sample (thermocouple 1, Fig. 2) a 1.7 °C increase in temperature was reported, while in the middle of the sample (thermocouple 2, Fig. 2) the temperature rise was 0.5 °C. In both cases, an abrupt increase in temperature was followed by its abrupt drop down, which is accounted for the thermocouples being exposed to the air in the cooling chamber immediately after the sample failure. In the remaining undisturbed lower third of the sample (thermocouple 3, Fig. 2), the temperature did not show any variations over the sample. An abrupt temperature rise by 0.5 °C was also recorded by thermocouples 5 and 7 (Fig. 2). In other locations of thermocouples, the temperature did not show any variations.

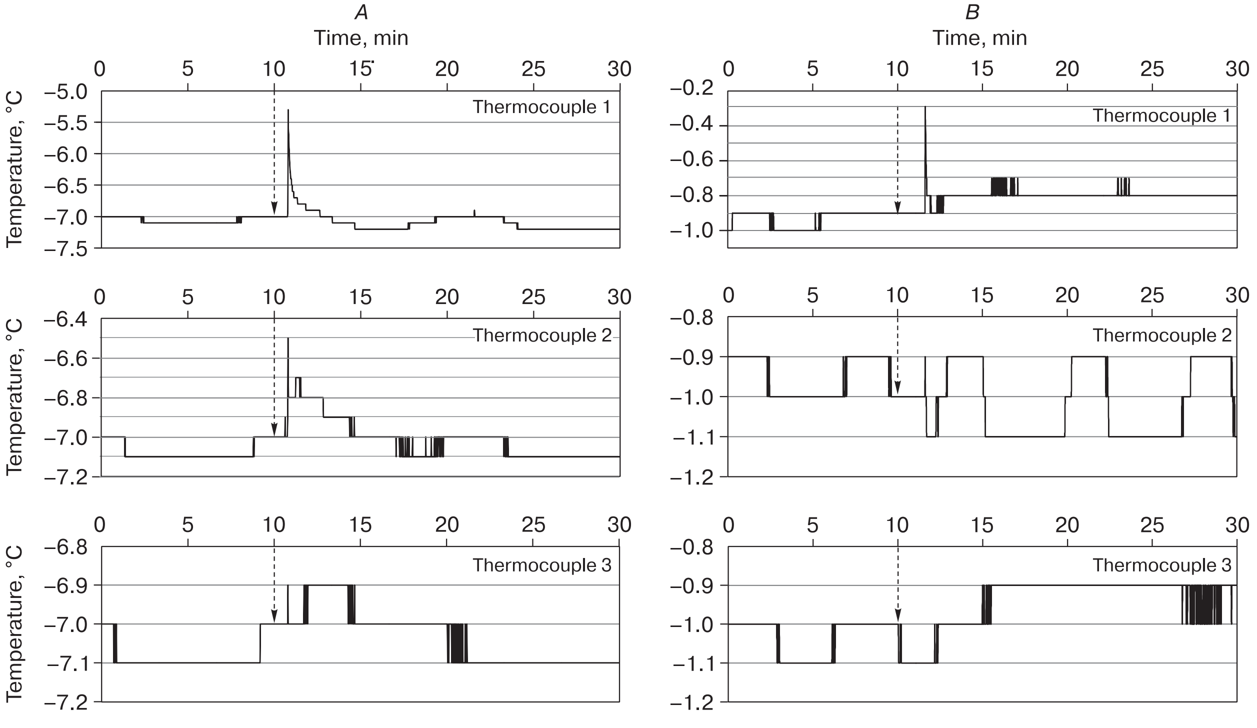

Fig. 6. Temperature variation in the samples of ice at rapid incremental loading and initial temperature: –7 °C (*A*) and –1 °C (*B*).

Arrow points to onset of loading.

At the time of the ice sample failure, which occurred at –1 °C (Fig. 6, *B*), the temperature abruptly increased by 0.6 °C only in the upper third of the sample. Whereas temperature variations were reported neither in the center, no in the lower third, no in any other points over the specimen's height. The creep curves for ice samples exposed to stepwise loading and at –7 and –1 °C are shown in Fig. 7. The corresponding temperature variation curves for the samples are shown in Fig. 8.

The plotted curves show that at –7 °C (Fig. 8, *A*) at the load stages corresponding to the attenuating creep, no temperature variations were reported from the ice sample. At the stage of sample failure (load exceeding 2.75 MPa), the temperature gradually warmed by 0.2–0.5 °C at different points of the sample. The temperature began to the rise in the ice sample at –1 °C (Fig. 8, *B*), once the load value reached 1.75 MPa. The subsequent temperature rises at different points of the sample varied between 0.1 and 0.3 °C. Note that at both initial temperatures the failure of ice samples proved viscous-brittle: more brittle at –7 °C and more viscous at –1 °C.

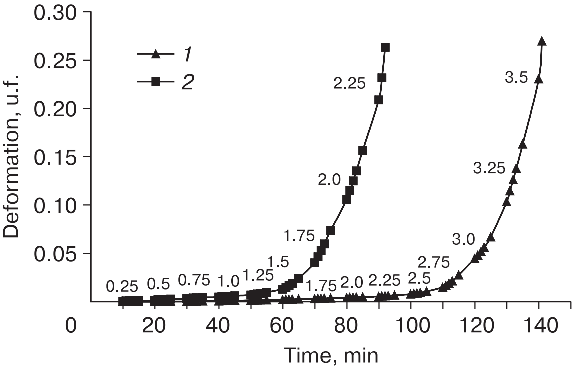

Fig. 7. Creep curves of ice at stepwise loading and temperatures: –7 °C (*1*) and –1 °C (*2*).

Numerals at the curves are the values of loading corresponding to steps, MPa.

CONCLUSIONS

The results obtained from testing the samples of frozen kaolinite clay under uniaxial compression exerted by constant strain of the loads applied show that at –7 °C a temperature rise was documented in frozen soil samples at the stage of their ultimate failure. At this, the greater the load inducing the sample failure and the greater the brittle failure of the samples, the greater is the temperature rise in the samples. This confirms the proposed hypothesis about the leading role of fracture-forming phenomenon in the manifestation of mechanocaloric effect in frozen soils under uniaxial compression.

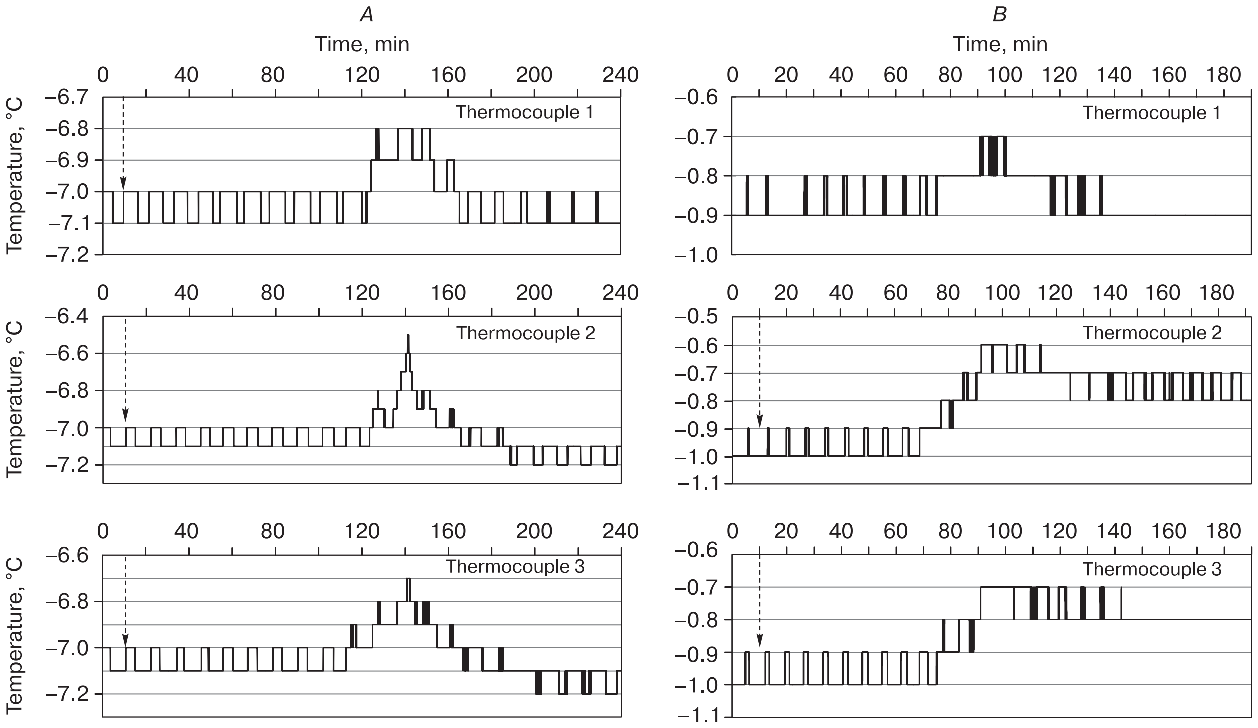

Fig. 8. Temperature variations in the sample of ice at stepwise loading and initial temperatures: –7 °C (*A*) and –1 °C (*B*).

Arrow points to onset of loading.

References

Gorelik, J.B., Kolunin, V.S., 2002. Periglacial Processes in the Lithosphere: Physics and Modeling. Izd. SO RAN, Fil. “Geo”, Novosibirsk, 317 pp. (in Russian)

Grechishchev, S.E., 1976. Some problems of thermorheology of frozen soils, in: Problems of Geocryology, Nauka, Moscow, pp. 122–142. (in Russian)

Grechishchev, S.E., Chistotinov, L.V., Shur, Yu.L., 1984. Cryogenic Physical-Geological Processes: Fundamentals of Modeling. Nauka, Moscow, 231 pp. (in Russian)

Kazakova, O.V., 1984. Mechanocalorical effect in clayey soils exposed to deformation, in: Cryogenic Physical-Geological Processes: Investigation and Prediction, VSEGINGEO, Moscow, pp. 86–91. (in Russian)

Konovalov, A.A., 1999. Gas hydrates and dynamics of permafrost at pressure changes. Geoekologiya, No. 3, 252–259.

Maksimyak, R.V., 1988. Structural processes and moisture transport in frozen soil under uniaxial compression, in: Mechanics of Frozen Soils: Thermodynamic Aspects, Nauka, Moscow, pp. 63–70. (in Russian)

Volokhov, S.S., 2016. Mechanocalorical effect in frozen soils under uniaxial compression. Earth’s Cryosphere XX (1), 29–33.

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