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PHYSICO-CHEMICAL PROCESSES IN ICE AND FROZEN GROUND

MECHANOCALORICAL EFFECT IN FROZEN GROUND UNDER UNIAXIAL COMPRESSION

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Mechanocalorical effect in frozen ground subject to uniaxial compression is studied in loading tests. The effect appears to be largely due to the growth of cracks.

Frozen ground, uniaxial compression, mechanocalorical effect, crack growth

INTRODUCTION

Ground temperature can change in response to stress and deformation, which is called a mechanocalorical (barothermal or thermomechanical) effect. In the case of frozen ground, this effect is associated with thermal rheology of frozen, freezing and thawing soils having specific relations of stress and strain with the temperature and phase composition of pore water [*Grechishchev, 1983*]. There have been relatively few experimental studies of these issues. Frozen bentonite clay, sand, and peat samples exposed to constant-rate uniaxial compression [*Grechishchev, 1976*] showed warming of 0.5 °C in clay, 0.7 °C in sand, and 1.0 °C in peat. The author explained it by coupled elasto-visco-plasticity (by analogy with coupled thermo-elasticity or strain-induced temperature changes in solids).

Wet clay silt paste in loading-unloading tests of Kazakova [*Grechishchev et al., 1984; Kazakova, 1984*] showed about 0.006 °C cooling and warming, which may result from heat intake and release, respectively, as water becomes free or bound.

Deformation of frozen shale in plate compaction tests [*Maksimyak, 1988*] caused cooling in the compaction zone beneath the plate, as melting of ice in the soil consumed heat, and warming in the zone of exothermic cracking under the plate edge and below the central compaction zone. However, *Maksimyak* [*1988*] did not specify the magnitude of temperature rise and drop.

Cooling during compaction of frozen soil samples was observed in tests of *Konovalov* [*1999*], as well as in those with frozen clay and silt (for 0.10–0.15 °C) reported by *Gorelik and Kolunin* [*2002*] who called it a barothermal effect and attributed to the ice-water phase change.

The mechanocalorical effect in frozen ground remains insufficiently investigated, especially its origin at different stresses and strains and its physical mechanisms. This study focuses on uniaxial compression of frozen clay and silt at different negative temperatures and loading conditions.

METHODS

Loading tests were applied to samples of deformed kaolinite clay (sandy loam) from Chelyabinsk city and silt from Bovanenkovo Village, Yamal Peninsula, with a total water content and density of 50 % and 1.55–1.56 g/cm^3 in clay and 20 % and 1.95–1.96 g/cm^3 in silt, respectively.

The employed updated KPr-1 testing systems consisted of cooling chambers (Fig. 1) and special devices (Fig. 2) that ensured vertical centering of samples and precise axial stress direction. Each instrument was equipped with clock-type strain gauges that measured deformation to an accuracy of 0.01 mm.

The temperature was maintained in the range +20 to –20 °C (±0.1 °C) and checked by *Testo-176-T4* loggers and seven thermocouples, to an accuracy of 0.1 °C (Fig. 3).

The soil samples were 90 mm high cylinders, 45.15 mm in diameter, with a rubber coat precluding sublimation. The thermocouples were set inside the samples through seven evenly spaced holes, 1 mm in diameter (Fig. 4): three 26 mm deep holes along the vertical axis (Fig. 4, *a*), to place the central thermocouple, and four 10 mm deep holes along the circle (Fig. 4, *b*).

Before the tests, the samples were placed into the loading system equipped with a strain gauge; the thermocouples were set in the holes and connected with the temperature loggers. The samples were not

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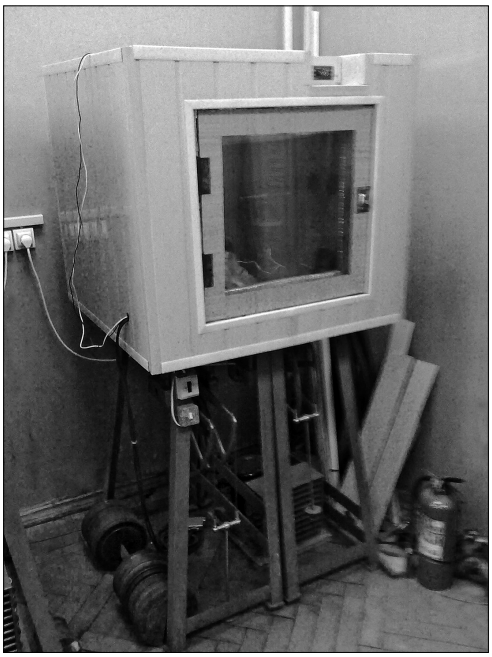

Fig. 1. Cooling chamber and uniaxial compression systems.

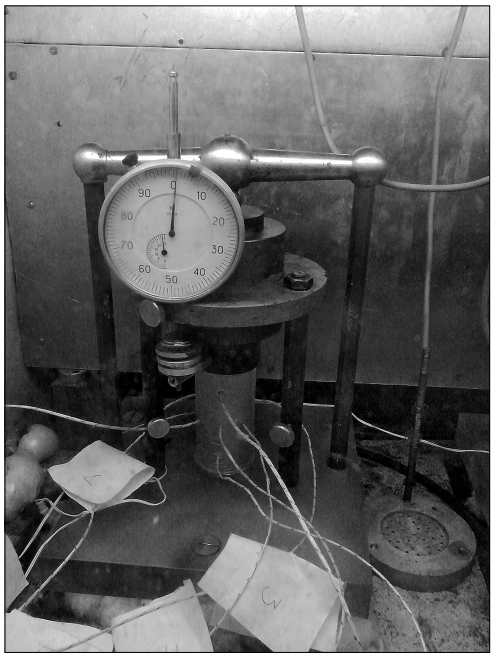

Fig. 2. System for uniaxial compression tests.

insulated. Each sample was kept at the experiment temperature for at least 24 hours.

The clay and silt samples were loaded incrementally (mode 1) and stepwise (mode 2). *Mode 1:* rapid incremental loading at 0.125 and 0.0615 MPa/s, at –7 and –1 °C, respectively, till ultimate failure. *Mode 2:* stepwise loading of 0.25 and 0.125 MPa steps, 10 min each, at –7 and –1 °C, respectively. All samples reached ultimate failure, except for frozen silt at –7 °C. Strain was measured at each step, 1, 2, 3, 5 and 10 min after the onset of loading.

The thermocouples placed in different parts of the samples took temperature at every 1 s (Fig. 4), starting 10 min before loading in order to estimate the initial temperature, the measurement error, and variance over the sample volume. The error did not exceed 0.1 °C; the initial temperature variations over the sample height and volume were within 0.2 °C. In most of tests, temperature was measured also after failure and unloading.

The results were plotted as creep curves in the case of stepwise loading and as temperature curves

Fig. 3. *Testo-176-T4* temperature loggers and a set of thermocouples.

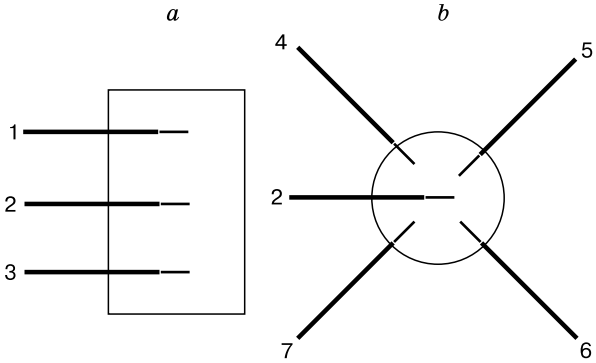

Fig. 4. Layout of thermocouples:

a – along sample height, *b* – in sample center; 1–7 are thermocouple numbers.

for all thermocouples. The temperature curves are discussed below for the central thermocouple (number 2). Loading started at a time point of 10 min. Temperature variations within 0.1 °C (before and during loading and during unloading) corresponded to the level of noise.

RESULTS

The deformation patterns observed in the loaded frozen clay and silt samples were as follows. Rapid incremental loading of frozen silt at –7 °C led to brittle failure along a major crack oriented at ~45° to the vertical generatrix. Stepwise loading of frozen silt stopped before failure, while frozen clay at the same temperature underwent viscoelastic failure with formation of cracks in the sample, both under incremental and stepwise loading. Before cracking, the samples deformed ductily and became barrel-shaped. At –1 °C, only frozen silt underwent viscoelstic failure under rapid loading, while frozen clay exposed to rapid loading and clay and silt exposed to stepwise loading deformed ductily and acquired barrel shapes, without visible cracking.

In the –7 °C rapid incremental loading tests, frozen clay and silt showed 0.3–0.4 and 0.4–0.5 °C warming after the maximum loading of 4.75 MPa for clay and 6.75 MPa for silt, respectively, and subsequent deformation for 8–13 min (Fig. 5, *a*, *b*). Warming was recorded at all points, with a difference of 0.1 °C. After failure and unloading, the samples gradually cooled down to the initial temperature.

Notable temperature change was observed in neither part of frozen clay samples exposed to deformation and failure for 1 min of incremental loading at –1 °C to 1.67 MPa (Fig. 5, *c*). Frozen silt exposed to such loading till 2.38 MPa and failure for 3.5 min be-

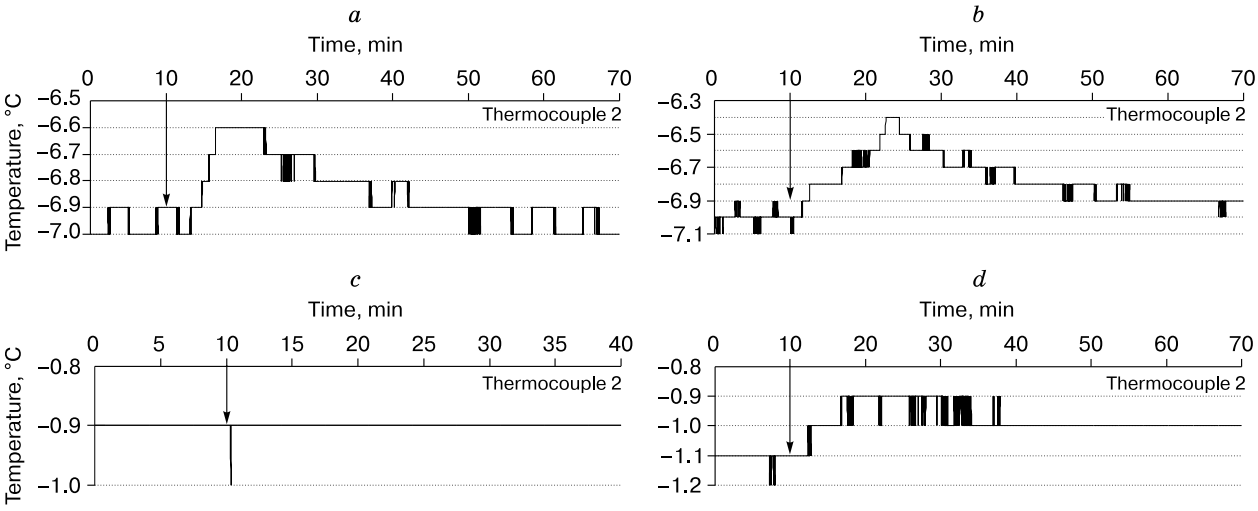

Fig. 5. Temperature variations in the center of clay (*a*, *c*) and silt (*b*, *d*) samples at rapid incremental loading.

Initial temperatures: –7 °C (*a*, *b*) and –1 °C (*c*, *d*). Arrow points to onset of loading.

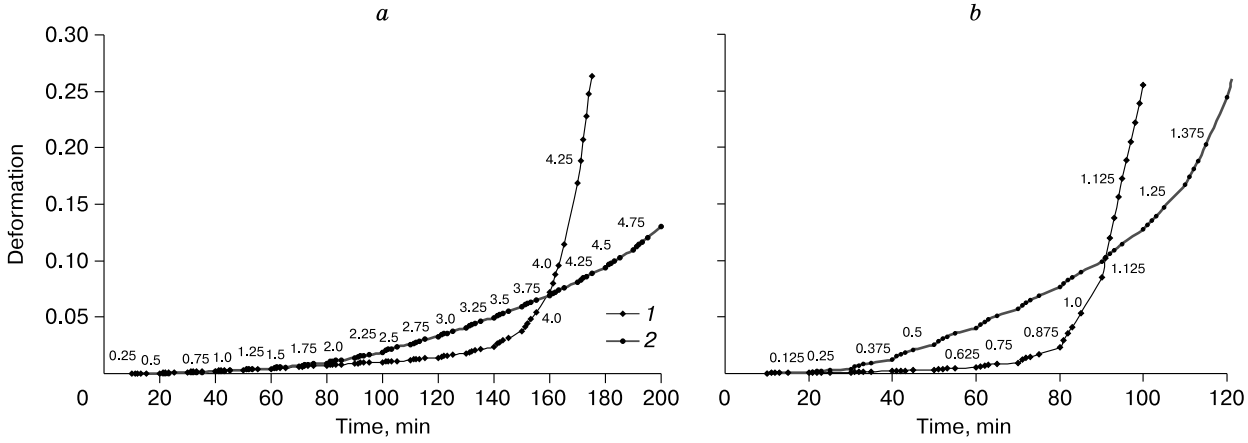

Fig. 6. Creep curves of frozen clay (*1*) and silt (*2*) at stepwise loading.

Initial temperatures: –7 °C (*a*) and –1 °C (*b*). Numerals at the curves are loading steps, MPa.

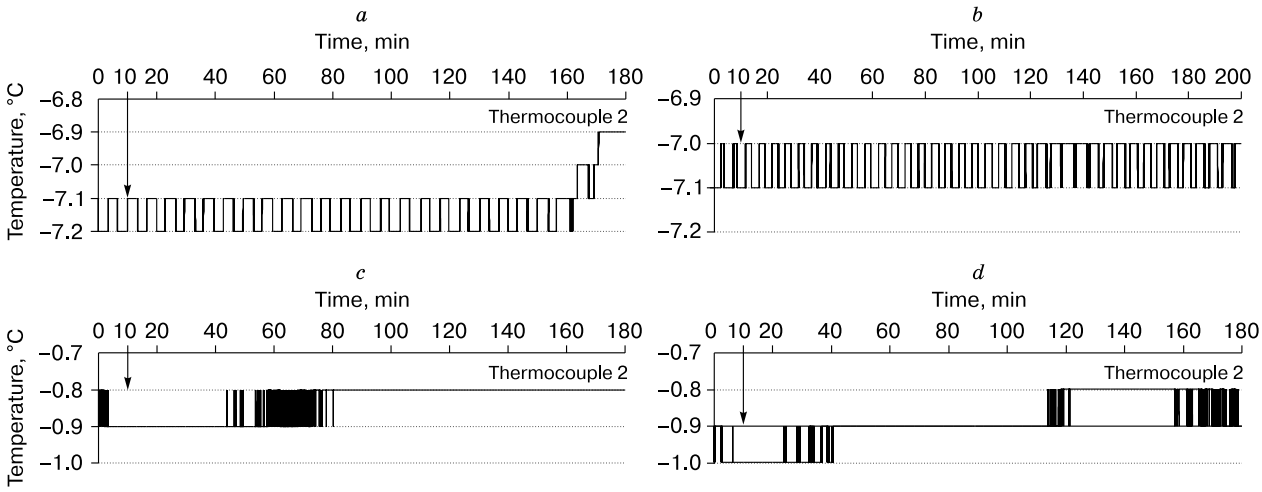

Fig. 7. Temperature variations in the center of clay (*a*, *c*) and silt (*b*, *d*) samples at stepwise loading.

Initial temperatures: −7 °C (*a*, *b*) and −1 °C (*c*, *d*). Arrow points to onset of loading.

came 0.1–0.2 °C warmer (Fig. 5, *d*), which was especially evident in the middle of the sample.

The creep and temperature curves for frozen clay and silt exposed to stepwise uniaxial compression at −7 °C are shown in Figs. 6, *a* and 7, *a*, *b*, respectively. Frozen clay did not change temperature upon loading corresponding to primary creep (Fig. 7) but became 0.2 °C warmer throughout the sample during failure as the load exceeded 3.75 MPa (Fig. 7, *a*). Unlike this, frozen silt, which did not reach ultimate failure, kept the same temperature (Fig. 7, *b*).

The creep and temperature curves for frozen clay and silt exposed to stepwise uniaxial compression at −1 °C (Figs. 6, *b* and 7, *c*, *d*, respectively) show almost invariable temperatures.

DISCUSSION

Thus, the samples of both frozen clay and silt responded by warming to rapid incremental uniaxial compression at −7 °C, and the mechanocalorical effect was more strongly pronounced in silt. In the case of stepwise loading, warming did not occur at the stage of primary creep but it did at the stage of secondary creep which led to brittle or brittle-ductile deformation.

In the −1 °C tests, the effect was observed in rapidly loaded silt which underwent viscoelastic failure but was absent in the case of plastic deformation, under both rapid incremental (frozen clay) and stepwise (frozen clay and silt) loading.

Thus, the mechanocalorical effect showed up in frozen soils which underwent brittle or brittle-ductile failure with cracking under uniaxial compression, but no such effect appeared in the case of viscous deformation and primary creep. Therefore, warming may be related with the formation of cracks.

Crack growth in solids is known to cause heating near the crack tip [*Parton, 1990*], the temperature rise reaching 130 °C in steel, 230 °C in plexiglass (PMMA), 1900 °C in glass, and 4400 °C in quartz. The heat comes from the surrounding material to the crack tip and is spent on plastic deformation and failure of the solid in its immediate vicinity.

Correlation between cracking and loading-induced temperature increase in frozen soils was also observed in compaction tests under the plate edge, in the zone of shear strain [*Maksimyak, 1988*]. In the tests described above, the effect was stronger in silt at −7 °C undergoing rapid brittle failure.

The observed uniform temperature increase at all points over the sample volume prompts that failure is preceded by the formation of microcracks at the stage of secondary creep; the microcracks then coalesce into major cracks along which ultimate failure occurs. Frozen soils warm up less strongly than unfrozen solids (for no more than 0.5 °C) because of slower crack growth and ice melting near the cracks. Ice melts as a consequence of warming and consumes heat, which cancels partly the mechanocalorical effect.

The stress-induced warming of frozen soil can be expected to increase the amount of unfrozen water in it and, subsequently, to accelerate secondary creep leading to ultimate failure. At the same time, opening of microcracks in frozen soils, and the ensuing formation of new surfaces, should cause cooling of the crack walls and thus produce local temperature gradients toward the crack tips. This may be one of factors responsible for migration of unfrozen water into cracks from their vicinity, whereby secondary creep slows down and the frozen soil becomes stronger and more stable to failure. This hypothesis is consistent with our previous results [*Volokhov, 2007, 2008*].

In conclusion, it is pertinent to note that self-heating of the material of thermocouples under loading cannot be responsible for the observed warming effect in frozen soils, as it is obvious from the stepwise loading tests for clay and silt at −7 °C (cf. Figs. 6 and 7). The mechanocalorical effect appeared in frozen clay loaded to 4.0 MPa and at a relative deformation of 0.07 but was absent in the case of 4.75 MPa loading of frozen silt deformed for 0.13.

The holes for thermocouples and the thermocouples themselves are man-made structure heterogeneities in frozen ground and concentrators of stress. Thus, they can be the source of crack nucleation in loaded soils, which is indicated implicitly by temperature increase at all measurement points. However, this pitfall of the experimental method cannot downplay the importance of the principal inference that cracking is one of triggers of the mecanocalorical effect. Natural frozen soils always bear defects and heterogeneities, which can become the foci of crack nucleation and growth and the related strain-induced heating.

CONCLUSIONS

1. Frozen soils can warm up in response to uniaxial compression, i.e., show the mechanocalorical effect.

2. The mechanocalorical effect in frozen soils exposed to uniaxial compression appears only upon brittle failure, at the stage of secondary creep, but is absent at viscous deformation.

3. The temperature increase under loading may be largely due to formation of cracks associated with failure.

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