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CONSTRUCTION ON PERMAFROST

TEMPERATURE DEPENDENCE OF STRESS-STRAIN PROPERTIES OF FRESHWATER ICE

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We present the results of experimental investigation of the temperature dependences of the stress-strain properties of freshwater ice and pykrete. It is shown that, as the temperature of freshwater ice decreases from −1.0 down to −6.0°C, the ultimate conditionally instant and long-term strengths of freshwater ice increase according to a linear law, whereas the temperature dependence of the viscosity coefficient is nonlinear. For a fixed temperature, the viscosity coefficient of the natural underground ice increases with its density and strongly decreases as the load increases.

Introduction

Various types of ice (including underground ice) are used for the purposes of construction for a long time [1]. At present, in connection with the intense development of construction in the Far-North regions, ice again attracts significant attention of experts as a structural material used, in particular, in the foundations of buildings [2-4]. Moreover, various ice-containing composite materials, such as pykrete [2, 5, 6] and ryzrete [5] now find extensive applications in the process of construction. However, the structural properties of ice are now studied quite poorly [7, 8]. As for pykrete and ryzrete, there are no comprehensive studies of the mechanical properties of these materials available from the literature.

Earlier, we performed experimental investigations of the dependences of the mechanical properties of frozen soils, ice, and ice-containing composite materials both on temperature and on their chemical composition [9-11].

Methods of Investigations

Ice specimens were prepared for testing by using the layer-by-layer freezing of cooled fresh water. In order to get the specimens of unstratified ice, it was necessary to substantiate the choice of thickness of frozen layers. For this purpose, we performed a preliminary series of short-time tests at fixed temperature for the uniaxial compression of cylindrical ice specimens with different thicknesses of frozen layers (1.0, 2.0, 4.4, 5.0, 10.0, 15.0, 20.0, and 60.0 mm). According to the results of these tests, we established the dependence of the conditionally instantaneous strength of ice σ_{inst} in uniaxial compression on the thickness of the frozen layers h (Fig. 1). It follows from the diagram that, as the thickness of the frozen layer increases from 5 to 15 mm, the strength of the ice specimen in uniaxial compression changes much slower than in the case where the thickness varies from 1 to 5 mm and from 15 to 60 mm. Therefore, for the preparation of specimens, we chose the most suitable thickness of the frozen layer equal to 10 mm. This value of thickness lies almost in the middle of the interval indicated above and turns out to be especially convenient for the production of tested specimens.

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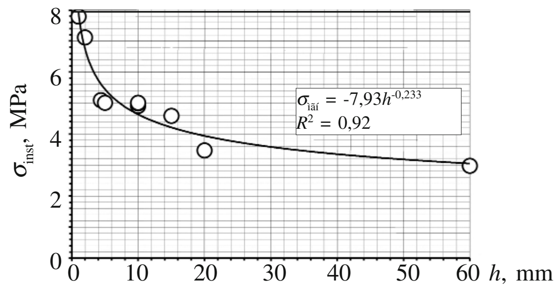

Fig. 1. Dependence of the ultimate conditionally instantaneous strength under conditions of the uniaxial compression on the thickness of frozen layers of freshwater ice at a temperature $T = -3^{\circ}$C.

To study pure unstratified ice, we chose the thickness of frozen layers for which the dependence of the strength of ice on the thickness of the layer is especially weak.

For the preparation of ice specimens, we used a metallic cylindrical form (frame) 120 mm in height with an inner diameter of 45 mm and a wall thickness of 4 mm. Cooled water (16 cm^3) was poured in this form by using a dozer. This water spread over the bottom of the vessel and formed a layer 10 mm in thickness. Then the vessel was placed in a freezer and held there for about 1 h at a temperature of -20°C. For this time, water was completely frozen and formed a layer of ice 10 mm in thickness. Then we additionally poured 16 cm^3 of cooled water into the form without removing it from the freezer and the vessel was frozen for 1 h once again at the same temperature. When the new layer of ice was formed, the procedure of pouring of water was repeated. The form completely filled with ice was held in the freezer for at least one day and then, also for one day, in a working chamber at $T = -3^{\circ}$C.

The finished specimen was measured and weighed to determine the density of ice. Then we placed it either in the testing chamber for preliminary holding at a temperature of subsequent testing or in the freezer, where it was kept at a temperature of -18°C.

The specimens of natural monolithic ice were produced in a somewhat different way. Ice monoliths delivered to the laboratory were sawed in the freezing chamber into prisms 150-180 mm in height. Then the prisms were used to cut out the specimens for testing by uniaxial compression. The specimens of monolithic ice were as large as 140-145 mm in height and 70 mm in diameter.

By the method of layer-by-layer freezing, we prepared 77 specimens of freshwater ice. In this collection of specimens, 51 specimens were used for short-time tests and 26 specimens were used in long-term tests. Nine specimens were made of natural monolithic ice.

The tests aimed at the evaluation of short-time strength were carried out according to the requirements of GOST 12248-2010. We used machines with pneumatic setting of the load and the admissible error of measurements varying within the limits ±0.004 mm. The long-term strength was measured by using a device AKR [with an applied force varying from 100 N to 6.5 kN and the limits of measurement of linear displacements (strains) of the specimen varying from 0.0 to 20.0 mm]. The short-time strength was measured by an IU-12 device (with an applied force varying within the range 600 N-22.0 kN and the limits of measurement of deformation of the specimen within the range 0.0-50.0 mm). The indicated devices are parts of a KrioLab experimental testing system (ETS) [12].

In the course of the tests, we take into account the increase in the cross-sectional area of the specimen under compression. In this case, the compensation of loading is introduced every time when the increment of the cross-sectional area becomes equal to 3%.

In order to determine the conditionally instantaneous strength in uniaxial compression, we imposed a continuous rapidly increasing load with steps whose duration did not exceed 5 sec. As a rule, this process of loading was terminated by brittle fracture.

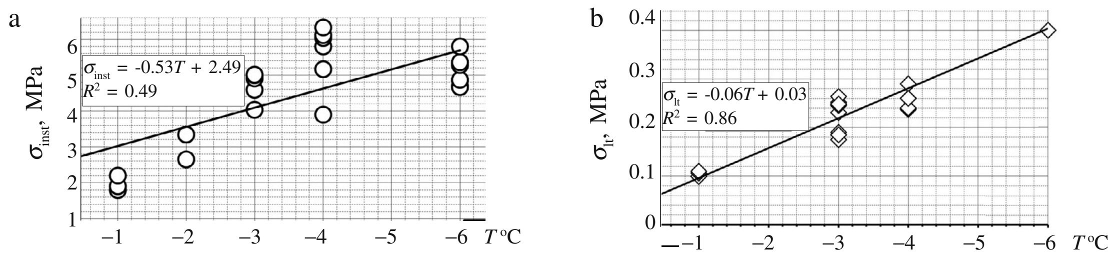

Fig. 2. Temperature dependences of the ultimate long-term (lt) strength of freshwater ice in uniaxial compression: a) σ_{inst}; b) σ_{lt}.

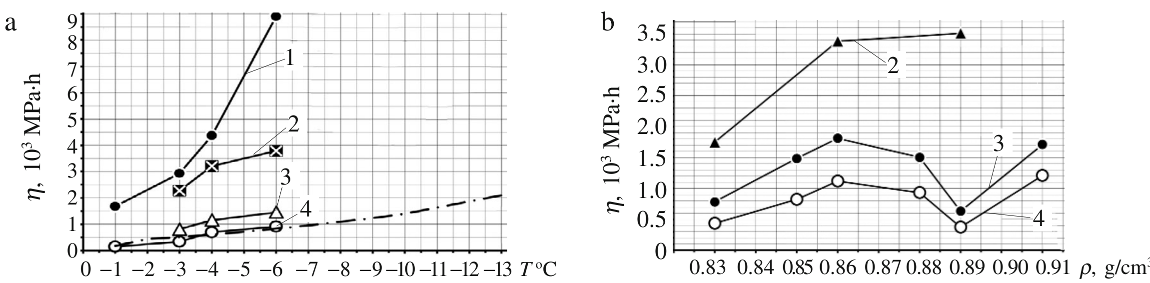

Fig. 3. Dependences of the viscosity coefficient under different loads (1 - 0.1 MPa; 2 - 0.2 MPa; 3 - 0.3 MPa; 4 - 0.4 MPa): a) on temperature for the freshwater ice with a thickness of frozen layers h = 10 mm; b) on density ρ for the natural underground ice; ▬ · ▬) according to BC 32-103-97.

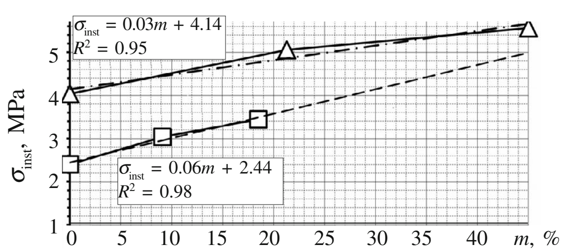

Fig. 4. Dependences of the ultimate conditionally instantaneous strength of pykrete in uniaxial compression on temperature and the paper mass m; △) T = –2°C; □) T= -3°C.

The long-term tests were performed until the transformation of the process of deformation of the specimen into the stage of undamped creep. The short-term tests were terminated when the longitudinal deformation of the specimen became greater than 20% of the initial height of the specimen.

The duration of long-term tests varied from 360 to 864 h.

Results of Experiments and Discussion

The performed series of tests of freshwater ice made it possible to construct the diagrams of temperature dependences of the conditionally instantaneous and long-term strengths of freshwater ice in uniaxial compression.

The obtained results show that the strength of ice increases according to a linear law as the ice temperature varies within the range from –1.0 to –6.0°C, (Fig. 2).

According to the results of the tests of ice specimens for uniaxial compression within the loading range 0.05-0.5 MPa at temperatures varying from –1.0 to –6.0°C, we determined the viscosity coefficients of freshwater and underground ice according to GOST 12248-2010 (Figs. 3 and 4).

In the diagrams, we can detect stable temperature dependences of the viscosity coefficients. In this case, it is necessary to take into account the nonlinear character of temperature dependences of the viscosity coefficient of ice.

For comparison, the experimental results are presented together with the data from [13]. As follows from Fig. 3, the viscosity coefficients presented in the building code (BC) [13] completely coincide with the viscosity coefficients measured in the present work under a load applied to ice equal to 0.4 MPa. First, this proves that the method used in our experiments for the determination of the viscosity coefficient is correct. Second, the fact that the data coincide demonstrates that the viscosity coefficients of ice given by BC 32-103-97 were obtained under a load close to 0.4 MPa. However, this fact is not mentioned in [13]. It is known that, as the load applied to ice increases, its viscosity coefficient decreases, which is completely confirmed by the results of our experiments (see Fig. 3). Therefore, it seems reasonable to present the information about the loads under which the viscosity coefficients of ice were measured in the normative documents specifying the corresponding coefficients.

The results of investigations also demonstrate that, at a fixed temperature, the viscosity coefficient of natural underground ice increases with the density of ice and strongly decreases, as the load upon the ice increases.

We also studied the strength of pykrete in uniaxial compression. Pykrete is a composite material prepared in the form of a frozen mixture of water and cellulose (sawdust, crushed peat, paper pulp, or dried algae) whose mass content varies from 18% to 45%. Pykrete thaws slower than ice and has a high strength. Moreover, it deforms under the impact load but does not cleave. Thus, it proves to be a suitable structural material under the conditions of Far North. For our experiments, we produced specimens of pykrete containing newspapers cut into strips 10 mm in width and 120 mm in length. The strips were placed in the metallic frame vertically along its axis. Then the water was poured into the frame layer-by-layer and frozen.

The results of measuring the strength of pykrete in uniaxial compression as a function of the content of paper and temperature are presented in Fig. 4. It is easy to see that the strength of pykrete linearly increases with the content of paper. As temperature decreases, the strength of pykrete also regularly increases.

Conclusions

The results of our experiments enable us to conclude that the strength of ice specimens produced by the method of layer-by-layer freezing decreases according to a power law as the thickness of a frozen layer increases. According to the obtained results, the most favorable thickness of the frozen layer is equal to 10 mm.

The experimental results demonstrate that, as the temperature of ice decreases from -1.0 to -6.0°C, the ultimate conditionally instantaneous and long-term strengths of freshwater ice increase according to a linear law.

We also reveal a stable increase in the viscosity coefficient of ice as temperature decreases. This dependence is nonlinear.

The viscosity coefficients presented in [13] completely coincide with the viscosity coefficients obtained in our tests under a load applied to freshwater ice, which is equal to 0.4 MPa. This confirms the correctness of the applied method intended for the determination of the viscosity coefficient.

Our results also show that, for a fixed temperature, the viscosity coefficient of natural underground ice increases with its density and significantly decreases as the load applied to ice increases.

It seems reasonable that the normative documents specifying the values of the viscosity coefficients of ice should necessarily contain the values of loads applied to the specimen for which these coefficients were measured.

It is experimentally demonstrated that the strength of pykrete in uniaxial compression linearly increases both with the content of paper mass and with a decrease in temperature.

REFERENCES

1. B. I. Vtyurin, *Recommendations on the Procedures of Investigation of Underground Ice and the Cryogenic Structure of Permafrost Soils* [in Russian], Gosstroi SSSR, Moscow (1969).
2. S. G. Gevorkyan, "Cryolite zone as a subject and territory of border conflicts," *Prostr. Vremya*, **3**, No. 1, 14 (2013).
3. F. D. Mubarakshina and M. R. Salyakhova, "On the history of the problem of buildings made of snow and ice," in: *Creative and Innovative Approaches in the Education, Science, and Art* [in Russian], Professional. Nauka, St.-Petersburg (2017), pp. 290-296.
4. L. I. Faiko, "Experience of construction of large ice objects," *Mater. Glyats. Issled.*, Issue 68, 104-106 (1990).
5. A. V. Ryzhenkov, "Pykrete and ryzrete. Unusual materials for the cold climate," *Klim. Priroda*, No. 3 (16), 29-33 (2015).
6. Yu. Semenov and S. Filin, "Innovative technologies of the application of ice-composite materials in the construction and operation of floating objects," *Kholod. Biznes*, No. 7, 22-29 (2011).
7. V. V. Bogorodskii and V. P. Gavrilo, *Ice. Physical Properties. Modern Methods of Glaciology* [in Russian], Gidrometeoizdat, Leningrad (1980).
8. K. F. Voitkovskii, *Foundations of Glaciology* [in Russian], Nauka, Moscow (1999).
9. V. I. Aksenov, S. G. Gevorkyan, and V. V. Doroshin, "Dependences of stress-strain and physical properties of frozen sands on humidity," *Osnov. Fund. Mekh. Grunt.*, No. 6, 35-39 (2017).
10. V. I. Aksenov, S. G. Gevorkyan, and V. V. Doroshin, "Dependences of stress-strain and physical properties of frozen sands on their total humidity (iciness)," *Ecological Geology: Theory, Practice, and Regional Problems* [in Russian], Nauch. Kniga, Voronezh (2017).
11. S. G. Gevorkyan, V. V. Doroshin, and V. I. Aksenov, "Some results of the experimental determination of the dependence of stress-strain properties of frozen fine and dusty sands on their total humidity (iciness) and temperature," *Vestn. NITs "Stroitel'stvo"*, No. 1(20), 25-34 (2019).
12. *KrioLab ETS. Certificate of Correspondence to the Requirements of GOST 12248-2010, No. ROSS RU.ME20.N02286* [in Russian].
13. *BC 32-103-97. Design of Marine Coast-Protecting Structures* [in Russian], Transstroi, Moscow (1998).