ON THE DIFFERENCE IN THE PROPERTIES OF ICE IN COMPRESSION AND IN TENSION

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ON THE DIFFERENCE IN THE PROPERTIES OF ICE IN COMPRESSION AND IN TENSION

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As is known, ice performs worse in tension than in compression. However, the degree of difference in its properties for these two types of deformation has remained unknown, since no special investigations of this question have been described in the literature.* Because of the difficulty of preparing specimens and the lack of suitable equipment, the number of tensile tests of ice is very small, and no deformation diagrams for this type of loading exist at all. After special testing machines for ice had been built, it became possible to carry out the corresponding experiments, the results of which are presented below.

The ice for the experiments was frozen from ordinary fresh water in a basin measuring 1.5×4.0 m and 1.5 m deep, with cooling only from its surface. The crystalline structure of the ice was similar to the structure of an ice cover on a scale of $1:10$. In other words, the ice had an acicular structure, with the cross section of the vertically oriented crystallites equal to several millimeters.

The specimens for the experiments were prepared very carefully. To obtain a tensile specimen of the correct geometric shape, metal templates were used; when these were slightly heated, all inaccuracies and irregularities on the surface of the specimen were easily removed. After this, metal collars were placed on the heads of the specimen, where they were firmly frozen on without gaps. In this form the specimen was inserted into the grips of the testing machine. The dimensions of the tensile specimens were: total length (with heads) $L = 42$ cm, length of the straight portion $l = 22$ cm, cross section of the straight portion $a \times b \simeq 6 \times 12$ cm.

In preparing compression specimens, special attention was paid to the parallelism of the faces and to their uniform contact with the platens of the press.

The cross-sectional size of the compression specimens differed little from the cross-sectional area of the tensile specimens. The loading time was also approximately the same: 16 sec in tension, 11 sec in compression. The averaged test data for the direction of the force parallel to the freezing surface (perpendicular to the vertical axes of the crystallites) are given in Table 1.

It is evident from the table that the compressive strength of ice is almost 9 times greater than its tensile strength. The quantities Δl and E_g also differ

Fig. 1. Tensile diagram for ice

Figure 1: Fig. 1. Tensile diagram for ice

considerably.

Figure 1 shows the deformation diagram in tension; the recording is enlarged 30 times.** This diagram differs from analogous diagrams for other materials, for example for metals. For steel, the first part of the diagram—the segment *ab*—is a straight line and corresponds to elastic deformations described by Hooke' s law, whereas for ice *ab* is a curve convex downward. Such a form is exhibited by the curves we obtained earlier (^{1}) for the change in the rate of plastic deformation of ice. Consequently, pla—

* We do not take into account the few data on the strength of ice in compression and in tension, since they were obtained for different ice and under different experimental conditions.

** The recording was carried out mechanically and, as far as we know, on such a large scale for ice for the first time.

···plastic properties of ice appear already in the very first moments of loading. In this connection it must be borne in mind that the specimen had already been given an initial load equal to 5% of the breaking load. As the plastic deformation increases, the specimen offers it ever greater resistance (the phenomenon of strain hardening), and approximately halfway along the segment *bc* the plastic deformation passes into elastic deformation. With a further increase in the tensile force, in the segment *cd* the ice behaves elastoplastically, the share of elastic deformation amounting to more than 50% of the total deformation. Therefore, in the moments preceding failure, no necking is observed in the specimen, and rupture occurs suddenly, as in brittle materials (point *d*).

Fig. 1. Tensile diagram for ice

Because of the large role of shear-formation processes in the loading of ice and the strong dependence of these processes on the crystalline structure of ice, the form of the deformation curves of different specimens is not strictly identical. In some of them the segment *ab* passes at once into the upper part of the segment *cd*, and the elastic deformation proves to be weakly expressed. The strength limit of such specimens is approximately half the strength limit of the specimens in the example analyzed above. Specimens are also encountered in which the deformation curve in its plastic zone (in the segment *ab*) is not as smooth as in Fig. 1, but has small steps. However, the general regularity of the behavior of ice in tension is preserved: the share of the elastic energy of deformation is greater not at the initial, but at the subsequent moments of loading.

Table 1

Mechanical characteristics	Type of deformation	Type of deformation
Mechanical characteristics	uniaxial tension	uniaxial compression
Strength limit σ, kgf/cm^2	2.8	25.3
Magnitude of absolute elongation (shortening) Δl, mm	1.12	0.12
Deformation modulus E_g, kgf/cm^2	1200	13 000

Note: unlike the modulus of elasticity E, the deformation modulus E_g is calculated from the total (aggregate) value Δl.

Figure 2 gives one of the deformation diagrams of ice specimens under compression*, enlarged 100 times. The periodic curve in this figure consists of time marks with a frequency of 50 Hz. In contrast to the tensile diagram, the segment *ab* is very small and weakly expressed. This is explained by the fact that by the time recording of the deformation began, the shear processes in the crystals had already begun to die out, since before this an initial load equal to 10% of the breaking load had acted on the specimen for several minutes**. In other words, recording of the deformation curve in this case begins from the end of its segment *ab*. The segment *bc* is absent on the compression diagrams of ice in the direction perpendicular to the vertical axes of the crystallites. From point *b* up to the moment of failure (point *d*) the deformation grows almost linearly. However, this deformation is not purely elastic, but some fraction of it (decreasing as the strength limit is approached)

* The diagram was obtained with the aid of an inductive transducer; changes in the current in it during deformation of the specimen were recorded on the film of an MPO-2 loop oscillograph. This was done for the first time for ice.

** This time is necessary for fastening the inductive transducer and adjusting the apparatus recording the deformation.

strength, as well as under tension) is plastic deformation. This is indicated by the values of the modulus of elasticity E calculated for different moments of loading, which in most cases prove to be smaller than the values determined by dynamic methods.

Thus, the general character of the deformation of ice under compression is similar to that under tension in the sense that, under compression as well, the initial portion of the curve represents not elastic but plastic deformations of the

Fig. 2. Compression diagram for ice

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Fig. 3. Influence of the structure of ice on its properties under tension and compression

Figure 3: Fig. 3. Influence of the structure of ice on its properties under tension and compression

material, i.e., the behavior of ice under load is the opposite of that observed in metals.

Fig. 2. Compression diagram for ice

To answer the question of the reason for the great difference in the properties of ice in compression and in tension, it is necessary to take into account the structure of ice. As is known, it is a polycrystalline body with a comparatively large size of the grains composing it. During the growth of ice, neighboring crystals are in contact with one another not over their entire lateral surface, but only at separate places, as is shown schematically in Fig. 3a. The remaining part of the area is occupied by intercrystalline layers and cavities filled with foreign impurities and air molecules. Under tension, the force P_{tens} is resisted only by the strength of adhesion of the particles in the three bridges connecting two neighboring grains (Fig. 3b, 1, 2, and 3), i.e., only part of the specimen cross section is at work. The layers of crystals reaching the boundaries of the cavities will slide freely in opposite directions, somewhat changing the shape of the cavities and increasing their dimensions (Fig. 3b). At first this requires small forces (segment ab on the deformation curves), but then they must increase (segment bc); and finally, when the shear processes cease, the resistance of the ice to further deformation will be determined only by the elastic interaction of its particles and by the destruction of these bonds (segment cd).

Under compression, the initial sliding processes soon cease, since the cavities become closed (Fig. 3c), after which the entire transverse section of the specimen begins to work completely.

Thus, both the character of the curves of deformation and the difference in the properties of ice under tension and compression are well explained. Proceeding from this and from the experimentally determined difference in the strength of ice in compression and in tension (the compressive strength is 9 times greater than the tensile strength), it may be assumed that in freshwater ice that has not been subjected to the action of any external forces, about 90% of the cross-sectional area falls on intercrystalline layers and cavities, and only 10% of it consists of regions of direct bonding between neighboring crystals.

Fig. 3. Influence of the structure of ice on its properties under tension and compression

The degree of difference between the properties of sea ice in compression and in tension should change with the age of the ice, decreasing as its age increases.

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1. V. V. Lavrov, *ZhTF*, **17**, no. 9, 1027 (1947).

Note: Figure translations are in progress. See original paper for figures.