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STUDY OF INFLUENCE OF STRAIN RATE DURING TESTING FRESHWATER ICE STRENGTH AND CRACK-RESISTANCE BY CRACKING AND COMPRESSION

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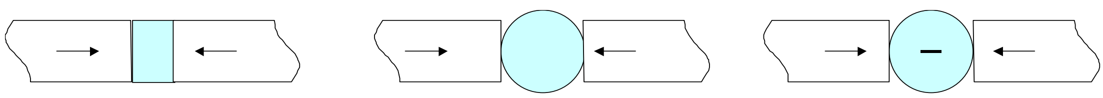
ABSTRACT

The paper presents results of study of ice strength properties and ice crack-resistance at dynamic compression and cracking. The dependence of freshwater ice sample strength on strain rate is presented. It is shown that static strength and dynamic strength of ice under compression are actually equal at strain rates up to $100 s^{-1}$.

Ice has unique physical features, such as unusual plastic properties, quasi-liquid surface layer, significant proton conductivity, completely-disordered hydrogen sublattice, etc. Besides, ice has 11 different phase states.

It is very difficult to test brittle materials by extension. Thus experts perform tests by cracking (the so-called «Brazilian trial»). These tests allow determining material strength at extension. Briefly, the essence of the tests is the following. A cylindrical sample is placed between ends of the bars (see fig. 1b) so that loading is provided along the generating line. Here uniaxial extension occurs in the central zone of the sample (along the diameter). Stress value is determined by the following formula: $\sigma_{ext} = 2P/\pi lD$, where P is the force of sample compression, D is its diameter, l is the length of the generating line.



a) b) c)

Fig. 1. Schemes of tests:
a) – uniaxial compression; b) – tests with disk sample cracking, so-called Brazilian trial;
c) – testing of crack-resistance

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Technology of preparation of ice samples

Various methods of sample production were tried. The method of cooling down and freezing of samples with one free surface appeared to be the most effective. Air bubbles formed during freezing were extruded from water. As a result, the produced samples were homogeneous and transparent.

Study of static strength of ice by compression and cracking

As a result of static tests, we obtained:

- average value of strength at compression σ_{compr} = 2.23 ± 0.3 MPa at T = -2 ÷ -5 °C;

- average value of strength at cracking σ_{ext}=0.46±0.11 MPa at T=-10÷-15°C.

Determination of dynamic strength and crack-resistance of small-size samples

Tests with small-size samples were performed at the facility [5] shown in figure 2.

This facility was rather simple. A rubber braid was used for acceleration of the bar-impactor. Titanium tubes having ∅16×1 mm were used as the bars. It was associated with very low level of signal (the force was 0.1…0.2 MPa). Similar to the static tests, the samples were cooled down by vapors of liquid nitrogen, temperature was controlled by thermocouple. High-speed video recording of the process of sample deformation and destruction was performed in the tests.

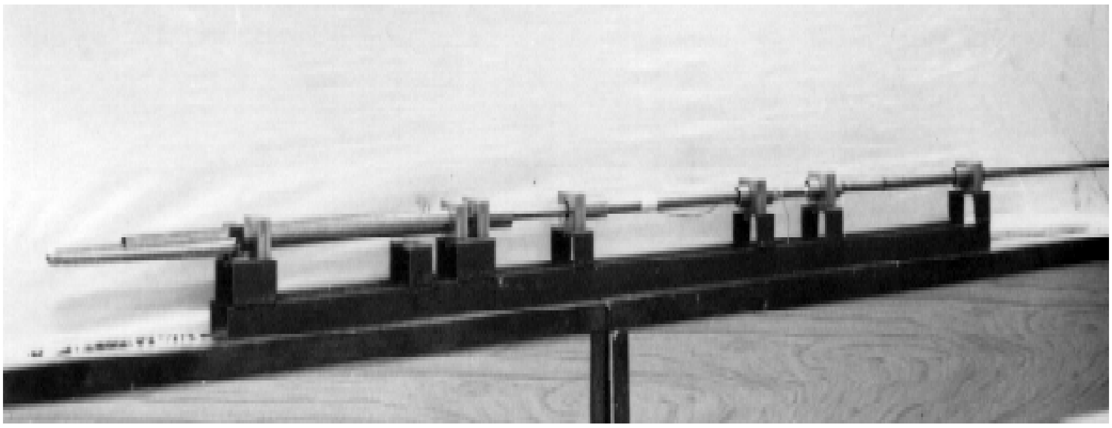


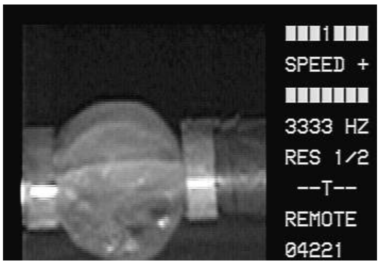
Fig. 2. Facility for dynamic tests by compression and crack-resistance testing

As a result of the tests, we obtained:

- average value of strength at uniaxial compression σ_{compr} = 2.2 ± 0.2 MPa at strain rate $\dot{\varepsilon}$ ~100s^{-1}. Diameters of tested samples were 20 ÷25 mm;

- average value of strength at cracking σ_{ext} = 0.42 ± 0.13 MPa.

Figure 3 presents photos of recording of the process of sample deformation and destruction.



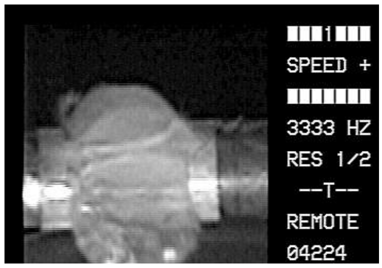


Fig. 3. Photos of high-speed video recording of ice sample testing by cracking (time between frames was 300 μs)

One can see in the records that destruction occurs due to formation of diametrical through crack passing through the all section of sample. The same character of destruction was observed in statics as well.

Ice crack-resistance

Tests with cracking and crack-resistance testing were very similar. The only difference was that the samples for crack-resistance determination had a diametrical through cut, which was made in the following way. During freezing, a thin steel plate was inserted in the sample. The plate width was ~6 mm. The plate was removed before test.

The crack-resistance coefficient K_{1d} was determined by the standard formula:

$$K_{1d} = \frac{P_Q\sqrt{l}}{BW} f\left(l / W \right),$$

where P_q – the critical force at destruction moment determined by the P–Δ diagram of sample compression, l – the initial length of crack, B – sample thickness, W – sample width (diameter), $f(l/W)$ – the calibration function.

As a result of the tests, we obtained value of the dynamic coefficient of crack-resistance. Average $K_{1d} = 0.89 \pm 0.37$ kPa × m$^{1/2}$ at T = 0 ÷-2°C and average loading rate of 170 s^{-1}. In the static tests, the average value of crack-resistance coefficient K_{1s} was equal to ≈ 1.2 ± 0.2 kPa × m$^{1/2}$. It is a little different from the dynamic coefficient of crack-resistance.

Study of dynamic strength of ice by compression of large-size samples

Of great importance is the problem of sample size influence on the strength characteristics (the so-called scale factor). As the first step in revealing this influence, we performed tests with dynamic compression of large-size samples. In these tests, sizes of samples were ∅ 60 mm, l= 12…60 mm. The tests were performed with use of the Split Hopkinson bar (SHB) method by explosive loading. Figure 4 shows the laboratory facility used in these tests.

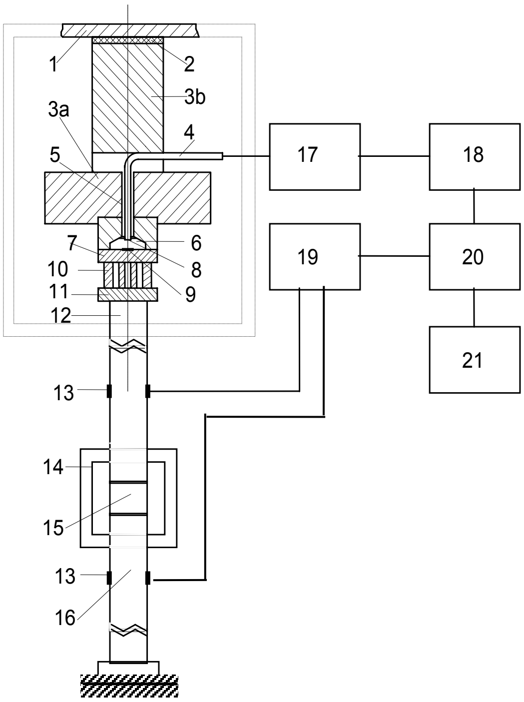


Fig. 4. Laboratory facility for SHB method: 1 – armor chamber, 2 – damper, 3a,b – support, 4 – detonation cable, 5 – filler inlet, 6 – spark discharger, 7 – impactor, 8 – insulator, 9 – aluminum punch crusher, 10 – transition disk, 11 – entering measuring bar, 12 – resistive-strain sensors, 13 – thermostat, 14 – sample, 15 – supporting measuring bar, 16 – detonating facility, 17 – synchronization unit, 18 – tensor station, 19 – recorder, 20 – industrial computer.

Diameter of the samples was equal to diameter of the bars. The tests were performed with samples having free side surface (uniaxial loading) and with samples placed in a rigid cartridge (uniaxial deformation). Typical diagrams of compression are given in figure 5.

A typical peak and smooth drop of stress caused by sample destruction were observed in the tests with samples without cartridge.

The dependence of ice strength on strain rate is clearly observed in three diagrams (see figure 5). In all tests, the loading conditions, diameter and technology of manufacturing were similar, but lengths of the samples were different. Therefore, strain rates were also different (in inverse proportion to sample length), i.e. the strength limit was increasing with strain rate growth.

When testing samples with ∅60 mm, the average value of ice strength was $\sigma_{str} = 4 \pm 2$ MPa at strain rate of $100 \div 360\ s^{-1}$.

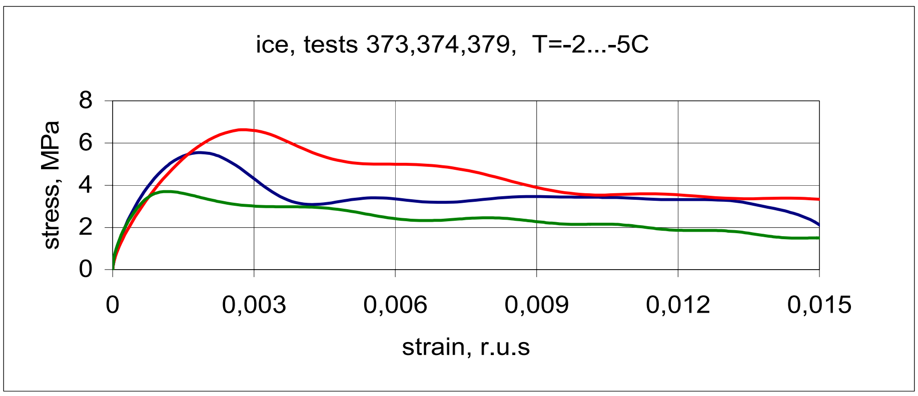


Fig. 5. Dynamic σ-ε diagrams of ice sample compression at uniaxial loading: 1 curve – sample with ∅56.7x16mm, 2 curve – sample with ∅56.7x12mm, 3 curve – sample with ∅56.7x25m

Figure 6 illustrates the dependence of ice strength limit on loading rate. All results of dynamic tests and the average value of the static tests are depicted in the diagram.
The obtained data can be well described by the approximating equation of the third exponential order: $P = -3E\text{-}7u^3 + 2E\text{-}4u^2 - 0.0172u+2.552$

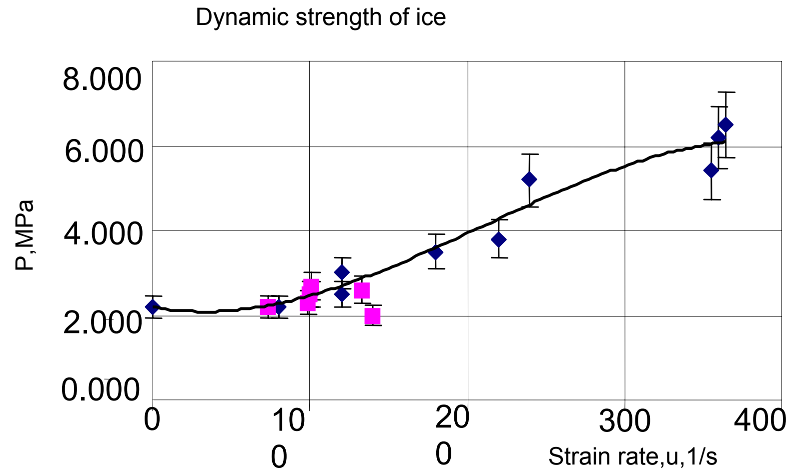


Fig. 6. Dependence of ice strength limit at compression on strain rate of samples

Basing on results of the performed work, the following conclusions can be made:

-for determination of ice strength by cracking, we used the so-called Brazilian trial in combination with the SHB method. Dynamic and static strengths at cracking were insignificantly different.

-we obtained experimental data on determination of ice sample strength at cracking and systematized them. Dependence of ice strength on strain rate in the range from 0 to 360 s^{-1} was revealed. This dependence can be well described by exponential equation of the third order.

-it is shown that the static and dynamic strengths of ice at compression are actually equal at strain rates up to 100 s^{-1}. Contrary to the static limit of strength, the dynamic limit of strength is approximately 3 times increased with strain rate growth up to 360 s^{-1}. The obtained results are in good agreement with results of the other works [1- 4].

Of great importance for the further work is study of scale effect allowing to use the results obtained by tests with small-scale models for nature objects.

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