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# Ice strengthening with stiffening techniques and chemical modification

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## ABSTRACT

The paper considers the methods of controlling ice strength properties by reinforcement and chemical modification based on systemic experimental studies. The effect of a number of reinforcing materials of different origins, chemical composition, morphology, dimensions of reinforcement was studied. In terms of bending strength, the ice beams reinforced with fibers were found to be effective, as the fibers improved the strength indices several times as many, the beams became flexible, and the destruction changed from instant to stepwise. The optimal values for the concentration and topology of reinforcement in the ice matrix were defined. The behavior of the destruction of freshwater ice cylinders under compression was studied experimentally and theoretically, also the influence of reinforcement on the destruction process was identified. The impact of chemical modification on the strength and tribological properties of ice as well as the possibility of combining chemical modification with the reinforcement of ice facilities were analyzed.

KEY WORDS Keywords: Ice strength; Ice composites; Ice reinforcement; Ice chemical modification

## INTRODUCTION

Ice is the most widespread natural solid-state formation in the Arctic zone (AZ) due to the fact that its significant part is made up of oceanic, sea, river and lake waters, and the cold climate contributes to the formation of ice. Therefore, it plays a major role in forming natural conditions and climate of the region; besides, the concept of "ice" is inextricably linked with the concept of humanity about of the Arctic. Its role is also important in the development of the AZ. On the one hand, ice impedes navigation, therefore, the use of icebreakers is required; another negative factor is the icing of equipment and structures, which can lead to failures and destruction. In this case, we need to "fight" with ice, but it can also be useful as a structural material, a coolant, and a keeper of information about the environment during ice formation, including the chemical, biological composition and temperature. An example of the construction application can be thousand years of experience by the Eskimos in the construction of ice dwellings (igloos). In our days ice is used to create ice crossings on rivers and lakes; winter roads through swamps and off-road; runways and landing sites; tipping sites on fast shore ice; ice moorages; artificial ice islands for drilling in shallow water; ice docks; cold storage facilities – it's hard to enumerate everything. The advantage of ice such as the possibility to produce it directly on site solves the logistics problem; while all other materials have to be delivered to the AZ from remote regions. Economically speaking, since there is plenty of water in the Arctic, and water is frozen under natural conditions, the advantages of ice as an Arctic material are obvious (Buznik et.al., 2017). However, other advantages apart, ice, like any material, has disadvantages, the main of which are as follows: limited temperature range of operation; low strength indices for a structural material and its fragility, accompanied by instantaneous destruction of ice structures. Undoubtedly, these disadvantages should be eliminated by improving the ice strength properties, which need systemic experimental and theoretical research.

It should be noted that the study of ice material is very complicated, the reason is the "capriciousness" of ice, because its properties at a considerable degree depend on conditions and technology of freezing, chemical composition of the solution to be frozen, the presence of various defects leading to agglomeration in ice as well as on the origin (marine, freshwater, atmospheric), conditions of its storage and operation and etc. The problem of a reference point, with which the strength indices of the test samples should be compared, stems from this "capriciousness". The article deals with the issues related to the development of the methods for improving the strength, tribological and operational properties of ice. The authors took part in the experimental studies of ice and ice composite samples, and the discussion is based on their results. The ice beams were tested using the three-point bending method compression of cylinders, which is important for understanding the processes that ice undergoes in real ice structures.

**Modes of ice strengthening and test methods**

After analyzing the literature data on ice strengthening, first of all, you should mark out the reinforcement with more durable fillers, which take on part of the external load, making the ice more stable and changing the behavior of destruction from instantly fragile to stepwise deformation. The introduction of reinforcement into ice transforms it from a homogeneous material into a composite one, in which the reinforcement is a filler, and ice is a matrix, which is designated as ICM (Petrovic, J. J. (2003), Vasiliev, et al. 2015). Reinforcing fillers can be of different chemical composition (metal, ceramics, polymers), different morphology (dispersed - 0D, fibrous - 1D, flat - 2D, three-dimensional - 3D), different origins (natural and anthropogenic); they can have different sizes relative to the ice matrix etc. As a rule, the chemical interaction of reinforcing fillers with ice is weak, and the reinforcement remains unchanged for a long time, keeping two phases in the composite - the matrix and the filler. In other words, the reinforcement affects the structure of the ice matrix only in the contact area, without affecting the structure of the ice in the main part of the matrix.

Systemic experimental studies of freshwater ice, as the simplest in structure, reinforced with various fillers, showed that the best strengthening of ice beams was reached when using inorganic (basalt, silicate, carbon) and polymer fibers (Grinevich, et al., 2020, Nuzhnyi-a, et al., 2020, Nuzhnyi-в, et al., 2020).

Another method of ice strengthening is a chemical modification; it has become widespread when creating ice surfaces in sports facilities, since it allowed regulating the tribological properties of ice, in particular for sliding on it (Goncharova, 2009). The essence of this approach consists in introducing the special substances (dopants) into the solution to be frozen; after dissolving in water the dopants form grains in ice during freezing (Goncharova, et al., 2020).

**Optimal reinforcing of ice beams with fibers**

Many ice facilities used in the AZ during operation undergo a bending effect, which is easy to study using the method of three-point bending of beams (Grinevich, et.al., 2020, Nuzhnyi-a, et.al., 2020, Nuzhnyi-в, et.al., 2020). The best strengthening is reached when the fibers are laid along the beam; during transverse lying the deformation curve fully corresponds to the curve of an unreinforced sample; and when lying at an angle, the fibers become guiding for cracks. At maximum tension ($\sigma_{max}$, ~2 MPa) and deflection (($\varepsilon_{max}$, ~1 mm) the ice beam collapses instantly forming a smooth transverse fracture (Fig. 1a). On deformation curve $\sigma = F(\varepsilon)$ this is illustrated by the break of the diagram (Fig. 1b, green line). The introduction of reinforcing fibers into the ice beam changes the strength parameters of the beam, which is clearly seen on the deformation curves. Thus, the presence of two layers of 5 polymer fibers increases □max up to 3 MPa, and after the appearance of a crack in the ice matrix, the beam does not break down and a residual strength is observed. The destruction of the composite takes place at 12 mm deformation (Fig. 1b, red line). An increase in the number of fibers in one layer up to 25 increases the residual strength up to 6 MPa and the deformation up to 33 mm (Fig. 1b, blue line). It was found that at the first stage the residual strength grew rapidly with an increase in the number of fibers, after that the growth rate decreased; seven fibers in a layer could be considered to be optimal.

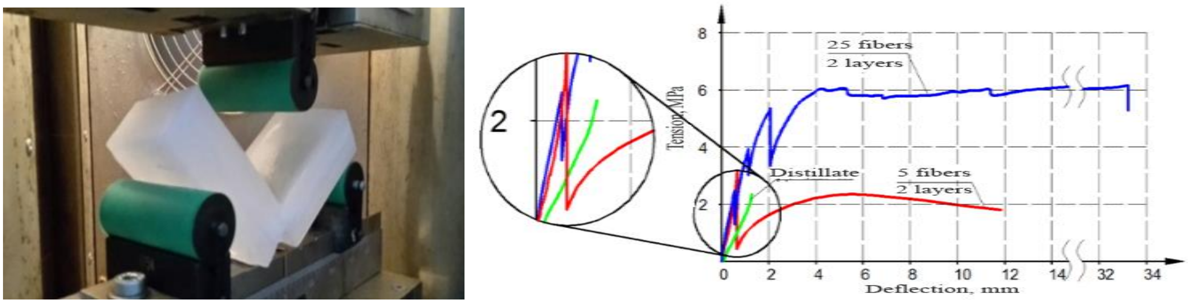



Figure 1. Image of a broken ice beam (a) and deformation curves of distillate ice beams b, green) reinforced with aramid fibers (b, read, blue)

Fig. 2a shows the deformation curves of composite beams reinforced with basalt layers of seven fibers in one layer; the sample strengthening is noticeable with an increase in the number of layers; in the 9-layer sample the residual strength reaches 17 MPa. Diagrams demonstrate that it shouldn't be necessary to use the maximum number of layers; a three-layer sample shows good indices, its strength is slightly inferior to the 9-layer sample, but saving in reinforcement is obtained. An important strength parameter of the beam is the specific strain energy (SSE), which is the work needed for breaking the ice sample. In the case of unreinforced ice, it is 3 kJ / m3, and for ICM beams it is two orders of magnitude higher (Fig. 2a).

The deformation under bending has an alternating character - in the bottom part there is tension, and in the top part - compression; besides, their numerical parameters are different. Therefore, the effectiveness of the reinforcing layer will be different depending on the zone where it is located. It is seen from the deformation curves in Fig. 2b that the layers in the bottom part of the beam (in the tension zone) are more effective.

Based on the above-mentioned, the rules for design of the most solid ICM beams with fibrous reinforcement can be formulated.

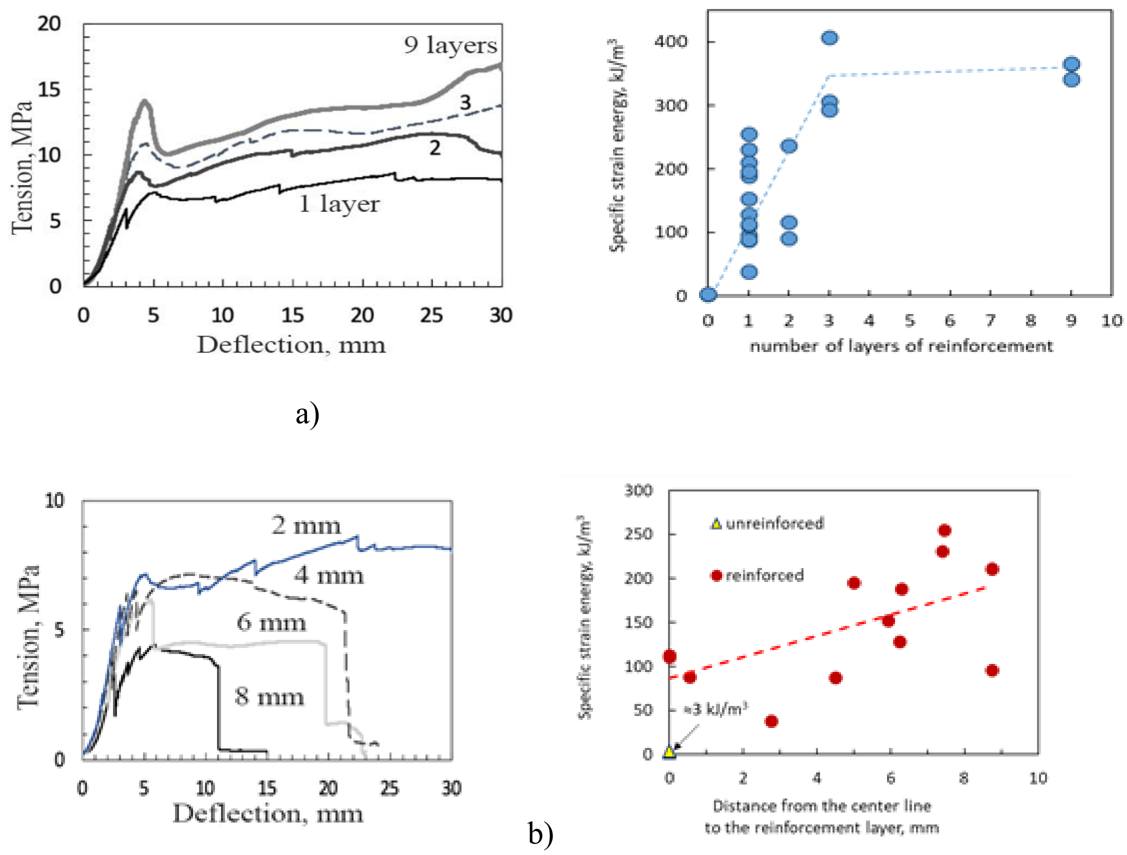



Figure 2. Nature of deformation curves of composite beams reinforced with basalt fibers, and dependence of specific strain energy (SSE) on the number of layers (a); deformation curves and SSE dependence on the location height of the reinforced layer in the ice matrix (b)

Fig. 2a shows the deformation curves of composite beams reinforced with basalt layers of seven fibers in one layer; the sample strengthening is noticeable with an increase in the number of layers; in the 9-layer sample the residual strength reaches 17 MPa. Diagrams demonstrate that it shouldn't be necessary to use the maximum number of layers; a three-layer sample shows good indices, its strength is slightly inferior to the 9-layer sample, but saving in reinforcement is obtained. An important strength parameter of the beam is the specific strain energy (SSE), which is the work needed for breaking the ice sample. In the case of unreinforced ice, it is 3 $kJ/m^3$, and for ICM beams it is two orders of magnitude higher (Fig. 2a).

Since chemical modification affects the grain size of ice, it is possible to regulate the strength properties of ice by analogy with metals that also have a grain structure. Fig. 3 shows the deformation curves of ice beams reinforced with two layers of basalt fibers. They differ in that the sample corresponding to the dark diagram has the ice matrix chemically modified. As can be seen, the modification improves the strength in terms of tension and deformation indices. SSE is at least two times less for a sample without modification of the matrix. It is obvious that the combined use of reinforcement and chemical modification can allow getting an additional strengthening effect.

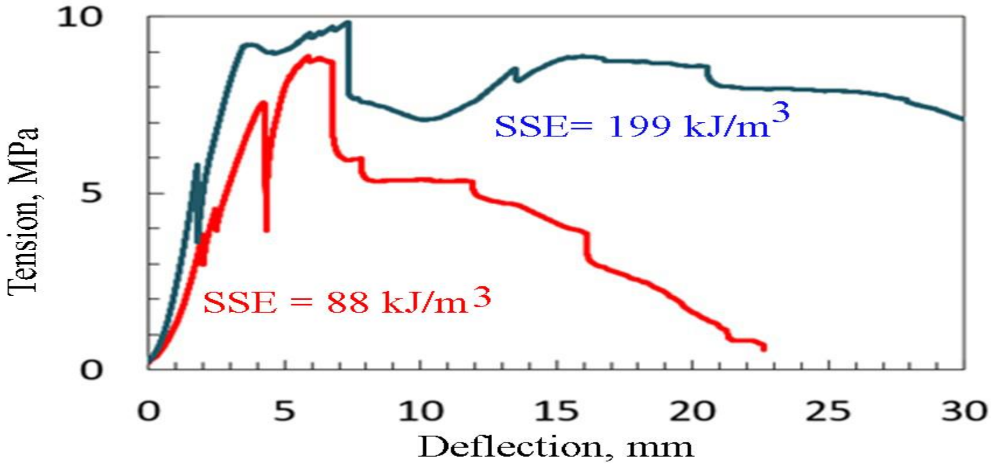



Figure 3. Deformation curves of the ICM beam reinforced with two basalt fiber layers: red line – without chemical modification, dark line – modified with the mixture of dispersed polytetrafluoroethylene, organosilicon oils and emulsions in a ratio 1:1:1, organosilicon oils and emulsions in a ratio 1:1:1

The second feature of fiber-reinforced ICM beams is a change in the behavior of destruction. If in the case of an ice beam a brittle fracture occurs with one transverse crack that appears in the tension zone (Fig. 1a) and goes to the top part of the beam, then the destruction of a ICM beam is phased and more complicated (Fig. 3). On the deformation curve several temporary phases of destruction, the photographs of which are given, can be distinguished. At the first phase, a vertical crack appears in the ice matrix under the movable punch in the tension zone. Further, the number of such cracks increases and a main crack appears at an angle to the movement of the punch (phases 3 and 4), which leads to longitudinal lamination of the composite during subsequent phases. It is important that after the cracks appearing, the composite keeps its overall integrity, and destruction takes place along the ice matrix within a certain time, about 10 minutes. The latter plays a significant part in practice at road maintenance, operation of crossing, unloading and landing sites on sea blocks of ice.

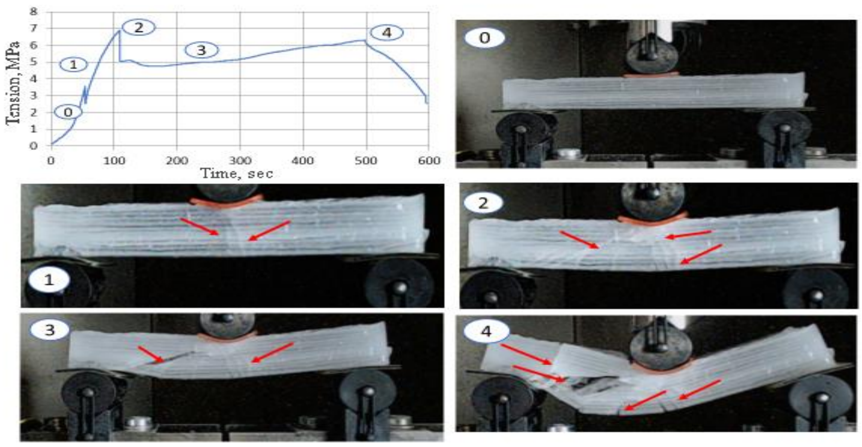
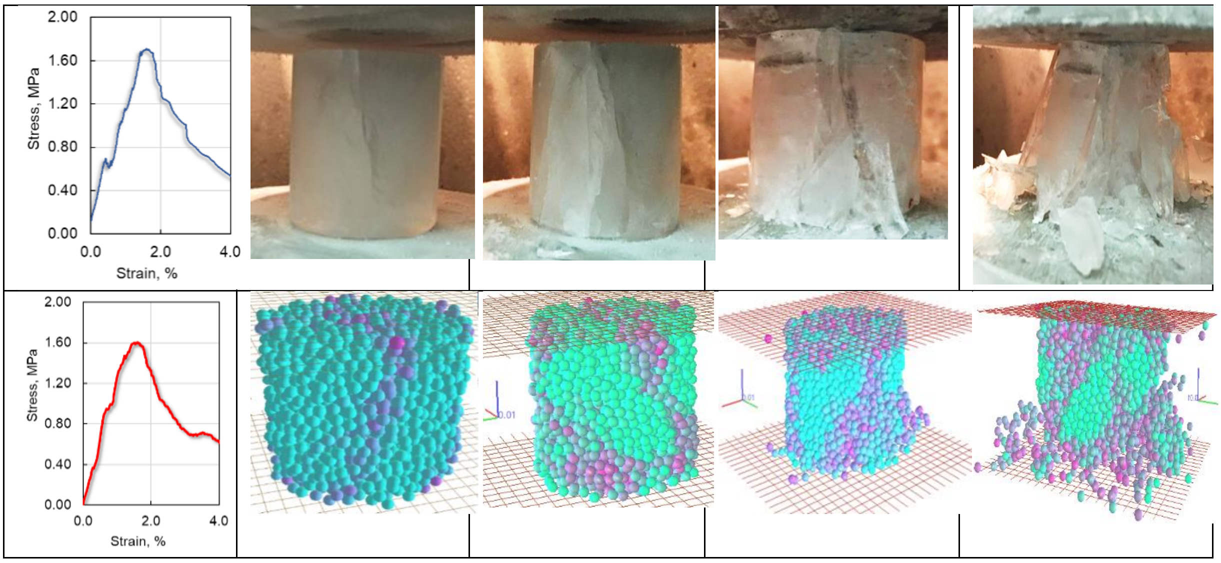



Figure 4. Deformation curve and cracking phases of the ice beam reinforced with two basalt layers in bottom and top zones

## Compression test for ice cylinders

To study the behavior of ice under compression the cylindrical samples of freshwater ice fabricated by volume pouring and layer-by-layer freezing were used (Nuzhnyi -b et al., 2020-6); the layer-by-layer frozen samples showed higher strength properties. As can be seen (Fig. 4, first line), at deformation by 0.57%, (decrease in the height of the cylinder) a vertical crack appears on the side of the movable rod, this crack becomes a through one. At further loading, other cracks appear and the cylinder transforms into an agglomerate of individual ice columns, which disintegrates as loading.

Numerical calculations of the destruction of the ice cylinder allow knowing about the observed features and the mechanism of destruction. The ice model was plotted using the discrete element method (DEM), according to which a continuous object was represented as a set of spherical elements connected by virtual beam bonds (Potyondy, et al., 2004). The Yade software package (Šmilauer, et al., 2004), which is successfully used when calculating concrete objects (Šmilauer, et al., 2010), was applied for plotting the model of bound particles, taking into account the damage of bonds between the elements. We tested it for ice cylinders. Physical parameters such as density of discrete elements, modulus of elasticity of element bonds, Poisson's ratio of element bonds, value of cohesion, angle of internal friction, ultimate elastic deformation, relative plasticity value should be set for calculations. We took them from the experimental data on ice. The correspondence between experimental and calculated data to a large extent depends on the successful selection of these data.

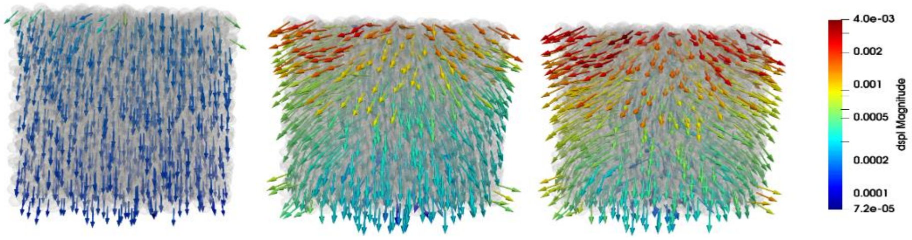



(a) (b) (c) (d) (e)

Figure 5. Experimental (top row) and theoretical (bottom row) deformation curves of compression of ice cylinders (a) and images of their destruction at different degrees of deformation (b - e)

The behavior of the calculated model samples is presented in the second row of Fig.5. Green spheres represent elements, between which the interaction of virtual bonds is kept, and violet spheres - elements with broken interactions (partially or completely). There is a good agreement between the calculated and experimental deformation curves and the behavior of the destruction of the cylinders. At first, small local cracks, which correspond to jumps and oscillations on the deformation curve, are formed. After that, vertical cracks are formed passing through the sample (Fig.5, line 1), then they are developing and increasing in the number (column 3); whereupon some parts of the cylinder begin to split off and separate from each other (column 4), all ends with the crumbling of the sample (column 5).

The used computational approach makes it possible to evaluate the motion of separate discrete elements under applied loading (Fig. 6). It can be seen that at small deformations, the model elements move exclusively in the direction of the applied tension. At large values of deformation, horizontal vectors appear; they increase that is reflected by the color of the vectors. This situation should lead to a reshaping of the cylinder – it flattens, and the cracks open.




a) b) c)

Figure 6. Moving elements in the model: ( $\varepsilon$ =0.52%, (b) $\varepsilon$=1.57%, (c) $\varepsilon$ = 3.66%

(a) (b) (c)

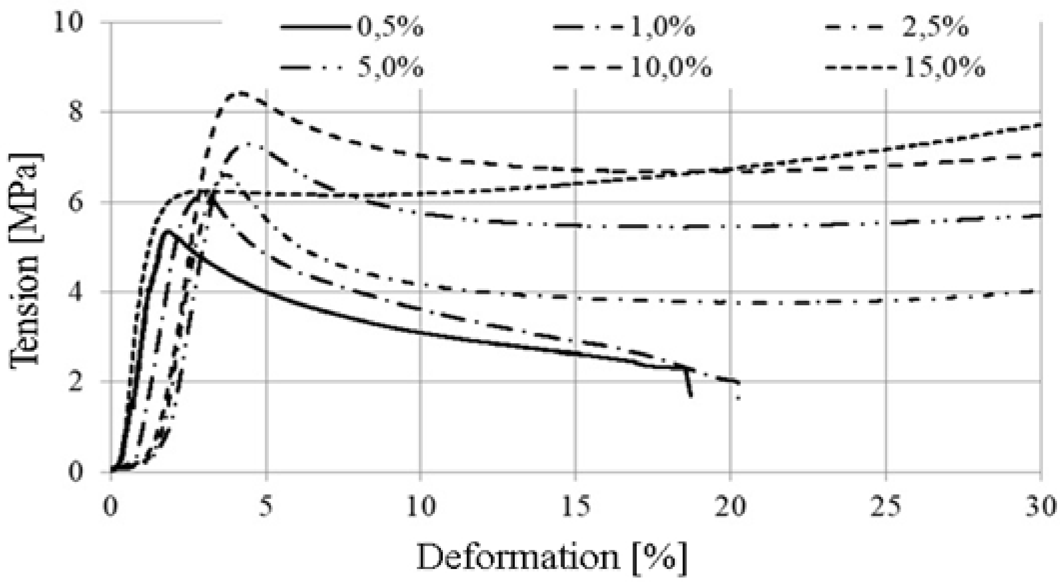



Figure 7. Ice cylinders with 10% sawdust filling subjected to axial compression at a speed of 3 mm / min (a) and 10 mm / min (b); a processed sample of an ice cylinder reinforced with hay (c) and deformation curves of composite ice cylinders for various concentrations (d)

The strength of ICM cylinders increases in comparison with the ice ones, while the dependence on the concentration of containing filler is observed. For sawdust, the optimum value is about 10%. The destruction of composites is different from that of ice and depends on the rate of applied tension. At low rates (Fig. 6a) the cylinder can decrease its height by 30% with an increase in the diameter. Cracks appear when the rate increases, but the integrity of the sample is kept (Fig. 6b). Hence, unlike pure ice samples, ICM samples are deformable, keeping a nearly cylindrical shape and integrity.

**Conclusion**

Systemic studies of the strength properties of composite ice beams made it possible to identify the best reinforcing and modifying components in terms of chemical composition and morphology, as well as to determine their optimal number and arrangement in the ice matrix. Actually, the formulae for both the technology of obtaining ice composites with enhanced strength characteristics and the selection and arrangement of fillers have been developed. This allowed in principle improving the strength properties of a number of ice structures listed in the beginning of the article. However, before applying the formulae under real Arctic conditions, tests of large-size ice composites were needed. For this purpose, the plates of freshwater ice modified and reinforced with basalt fibers at dimensions of ~ 6,000*2,000 mm and thickness from 70 to 50 mm were made, placed on two supports and then studied. The construction withstood the repeated passage of a car weighing ~ 3,800 kg at temperatures from minus 15 °C to plus 5 °C in the rain. The deflection of the ice plate was of 25-30 mm, but kept its integrity, this indicated that the approach offered was promising under real conditions. As for the chemical modification of ice, some Continental Hockey League clubs and skating centers are already using the developed formulae when pouring with water the tracks to form ice for lugging and bobsleighing and hockey fields.

The behavior of ice cylinders with different fillers and filler free was experimentally studied under axial compression, which made it possible to define their strength parameters and the nature of destruction. It was shown that the reinforcement with dispersed fillers significantly strengthened the ice cylinders and changed the nature of their destruction. An in-depth understanding of the nature of the destruction of cylinders was reached by computer calculations of the behavior of ice cylinders using a model of discrete elements. The obtained theoretical results agreed in quality with the behavior observed during the experiment.

The research has shown that components of ice composite material could be deformed and processed by bending and pressing, which was not possible in the case of pure ice.

Due to efficiency of strengthening freshwater ice it becomes tempting to apply the developed methods to sea ice, preferably under natural conditions, but the authors do not yet have such opportunities. Therefore, dynamic tests were carried out consisting in cyclic loading of large-scale fragments of freshwater modified and reinforced ice that were placed on two supports in a basin with seawater corresponding to the salinity of the Barents Sea. The deflection of a fragment at dimensions of 950 * 450 * 45 mm was 80 mm at a load of 210 kg, followed by the restoration of horizontal position when the load was removed. An optimal thickness of the additional layer, the concentration of dopants and the number of reinforcement layers depended on the value and method of applying the force load.

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