Piezooptical properties of ice

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Abstract. In connection with the use of ice as a building material, it is interesting to study its strength characteristics. To increase the strength of ice, the ice matrix was reinforced by adding various materials of natural origin. The greatest significance in this study is the assessment of the stress-strain state of ice composites. The possibility of the photoelasticy method application to obtain stress fields in ice composites was considered. Due to the lack of data about the piezo-optical properties of ice, we performed numerous studies in this direction. As a result of research, it was found that it is not possible to quantify the piezo-optical properties of ice, because ice has a low optical sensitivity, high brittleness, and the ability to melt at room temperature. It is possible to qualitatively characterize stress fields, identify stress concentrators, and describe the effect of reinforcing materials on the stress state of the ice matrix using the photoelasticity method. The use of ice-composite materials in the Arctic is a promising direction.

1. Introduction

In the Northern regions of Russia, ice crossings over rivers are actively used in winter. The equipment and maintenance of crossings have significant features, mostly due to the conditions of low temperatures and presence of snow and ice. The equipment of crossings in winter is affected by the mode and characteristics of the water barrier, the thickness of precipitation (snow), wind conditions, the presence of artificial drains and geothermal sources, etc. [1].

According to the weather forecast, about 1000 ice crossings are opened in winter each year. Most of the crossings are located in Siberia and the North-West of the country. One of the largest places of winter recreation and, at the same time, one of the largest crossings is lake Baikal (Figure 1). Every year at winter people come there from all over the country.

Due to the widespread use of ice crossings, there is a sufficient amount of researches aimed at improving of their strength and reliability. Various crossing options are being considered. One example is a bridge crossing from a pontoon park (crossings that are assembled directly on the ice from prepared ice plates with reinforcement), without submerging of ice cover section located under the bridge [1]. Experiments on the destruction of ice samples with surface reinforcement allowed us to determine the optimal thickness of ice protective layer [2].
The existing methods of crossings’ strengthening can also use the inclined thermosiphons. They provide artificial ice freezing on the natural ice cover. Vaporizers of thermosiphons, which are heat sinks, simultaneously act as reinforcing elements. After installing in the project position, the thermosiphons perform layer-by-layer freezing of artificial ice. The thickness of the frozen layer is selected by taking the required load capacity of the crossing into account [3]. It is known that the strength of artificially laid ice is approximately 30-35 % lower than the strength of ice formed naturally [4]. Accordingly, the ice frozen with the implementation of thermosiphon vaporizers also has a strength lower than the main ice, but this does not affect the carrying capacity of the ferry [5].

Recently, various research teams have been studying the strength characteristics of composite materials made of ice (CMI). I would like to focus on the works of scientists under the guidance of V. M. Buznik. These studies are aimed at identifying of dependence of changes in the strength of ice affected by its reinforcement with various fillers of plant origin (sawdust, etc.), in order to improve the strength characteristics of CMI for construction use in the Arctic areas. In the works of V. M. Buznik and his co-authors it is noted that the CMI with 15% wood sawdust reinforcement caused an increase in the strength due to reinforcing fibers while destruction of the ice matrix. It was found a 15-fold increase in strain. This makes CMIs of this type promising for practical application. Most samples were performed through layer-by-layer water filling (1-2 mm thick). About 500 samples (1000x500x50mm) were obtained and studied under conditions simulating those in Arctic. For fillers of natural origin, the highest strength was achieved when reinforced with sawdust with a mass content of 10 and 15 % [6].

![Figure 1. Photo of the ice cover of lake Baikal](image)

**Figure 1.** Photo of the ice cover of lake Baikal

It should be noted that when a crack forms in the ice matrix, the load drop is barely noticeable, which indicates good adhesion of the matrix and the filler, and that the NCMI already works as a material, not as a structure. Separately, you should pay attention to the mechanism of crack formation when applying reinforcing layers of "Rusar-S" strings (Figure 2,a). First, a crack is formed in the ice matrix under the puncheon, as in the classic version. It is stopped by the first reinforcing layer. As the load increases further, cracks appear asymmetrically in the stretched zone, and the central crack spreads to the next reinforcing layer. Then the cracks develop in the direction of the compressed area under the puncheon. In this case, the upper part of the sample, due to the blocking of the bending deformation by reinforcing layers, no longer works for bending, but for compression, and a transverse

![Figure 2. Sample reinforced with «Rusar – S» strings after bending test: a) front view; b) bottom view.](image)
force occurs in the sample, leading to the formation of longitudinal cracks (Figure 2,b). Thus, reinforcement with mesh fillers is considered promising [6]. Reinforced ice under compression tests can withstand 2-3 times higher loads compared to "pure" ice, and more than 4 times under high-speed and short-term loading [7]. The strength of reinforced samples is 1.4 times higher compared to non-reinforced ice, which is consistent with bending tests. The reinforcement prevents the samples from splitting into separate parts, as in "pure" ice [8].

All of the above is a prerequisite for the study of the stress state of the CMI. There are a number of methods for studying stress. To study the stress-strain state of optically sensitive materials, it is important to use the photoelasticity method, which is one of the non-destructive testing methods. This method can be used to solve linear and nonlinear problems, both physically and geometrically nonlinear [9].

Optical methods are used to study the mechanical behavior of materials because they provide full-field measurements. There are many suitable methods for this purpose, such as interferometric methods, digital image correlation (DIC), infrared thermography (IRT), and photoelasticity [10]. Using the nonlinear photoelasticity method, it is possible to study geometrically nonlinear problems of crack mechanics in the region of large elastic deformations [11-12]. It is also possible to obtain stress and strain fields, concentration coefficients when stretching rubber bands with a crack or lateral incision, and to present the results in Euler and Lagrange coordinate systems [13].

In general, stresses are determined either by known deformations or by numerical integration of differential equations of equilibrium [14]. Stress concentration is a point in structural elements defined by sharp transitions in cross sections associated with the presence of holes, fillets, incisions, etc., called stress concentrators. The degree of stress concentration is characterized by the concentration coefficient [15]. Separate estimation of stress concentration coefficients along the x and y axis can be useful for evaluating the strength of composite materials with a fiber structure [16]. The stress state of such elements has its own characteristics and there is not enough information about it in the technical literature [17]. One of the non-destructive testing methods is industrial tomography, which task is to restore the defect image using a reference sample [18].

When the test medium contains opaque areas that absorb probing radiation, it causes tomographic problem with incomplete projection of data. Such problems cannot be solved using traditional computed tomography methods that require a complete projection matrix [19].

Out of all the methods considered, one of the polarization-optical methods, namely, the photoelasticity method, was selected in the framework of this study. This method is suitable for the study of transparent materials, including ice. The photoelasticity method is relatively simple and allows you to get visual results. As far, as the technical literature was analyzed, there is no other, alternative method to study the piezo-optical properties of materials.

2. Technique of experiment

Research problem:

1. Development of techniques for making models from ice.
2. Determination of piezo-optical properties of ice using the photoelasticity method.

Tested different models of ice, such as: type 1 - disks 1 cm thick and 6 cm diameter; type 2 - rectangular plate with a thickness of 1 to 1.5 cm, with sides 6 cm ×3 cm; type 3 - a rectangular plate with a thickness of 2-3 cm, with sides 6 cm×10 cm.

In the course of experimental studies, 30 different ice samples were tested, including all the types previously marked. A wide range of sizes and thicknesses of the tested models allowed us to form a better understanding of the properties of ice.

The preparatory stage for this study took quite a long time, since it was necessary to find out what shape and thickness of the sample would be most convenient for the experiment. The models were filled in several ways:

- By a layer-by-layer filling method, 2-3 mm to achieve the most convenient thickness, while a large amount of time is required, since the solidification of one such layer takes about 3-4
hours in the freezer at a temperature of -18 degrees Celsius or 6-8 hours in the refrigerator at a temperature of 0-3 degrees Celsius;

- Through the method of one-time filling, in which the entire mass of water immediately filled the required volume, with this method, the time spent on solidification of the entire model is 5-6 hours, it is much faster, but the quality of filling is lower, since often with this method of filling there is an opaque area of the model, which is characterized by a high content of impurities (Figure 3,a). The water used for the experiments was different: ordinary water from the water supply, distilled water, triple-boiling water.

![Figure 3. a) Photo of the type 1 model before loading; b) Photo of the type 2 model before loading.](image)

The best transparency of ice was achieved using the method of layer-by-layer filling when adding soap to the triple-boiling water at a concentration of 5-10% of the total volume, it was used the model type 2 (Figure 3,b).

![Figure 4. a) Photo of the type 3 model before loading; b) - d) Photo of the type 3 model when the load increases from 0 kN to 0; 98 kN](image)

Before loading (Figure 4), we obtain clearly defined areas of different colors (such as yellow, green, and blue), which means that the models have stress concentrators. There is a pattern of interference bands indicating residual stresses. Loading was performed by static and dynamic methods [20]. The causes of stress concentrators may be air bubbles or the constricted expansion of water during solidification. After the destruction, when the model is passed through on the PPU-7 installation, it becomes possible to state the residual stresses that occur in the model during the destruction process. It is only possible to evaluate them qualitatively, but not quantitatively, since it is not possible to determine the price of a strip of ice by stress.
When conducting experiments on the PPU-7 installation, it was difficult to install models in the press, since the ice began to slide when melting, and this interfered with the qualitative study of its properties. It was decided to use a gauze pad along the contour of the model, that provided the friction between the model and the press. When filling, distilled water, the third type model, medical gauze, and a one-time filling method were used. During water solidification, the gauze was randomly distributed over the volume of the model (Figure 5), while the fibers remained in the planned place, too. There was an increase in strength characteristics. The models reinforced with gauze withstood the load 2.5 times higher than the other models (without the introduction of gauze). Thus, the gauze has become a good reinforcing material, it is evenly distributed over the model, this contributed to the preservation of the shape. Strength has increased. Splitting into individual fragments occurred in a smaller volume compared to non-reinforced models. In this case, the model has partially preserved its structure and shape.

![Figure 5. Photo of a type 2 model reinforced with gauze after being destroyed.](image)

3. Results of the work
1. As a result of research, it was found that it is not possible to quantify the piezo-optical properties of ice, because ice has a low optical sensitivity, high brittleness, and the ability to melt at room temperature. It is quite possible to characterize stress fields qualitatively, identify stress concentrators, and describe the effect of reinforcing materials on the stress state of the ice matrix using the photoelasticity method.
2. It was found that ice has low piezo-optical sensitivity, which is insufficient for quantitative assessment of the ice composite stress state, but is quite acceptable for qualitative description of stress fields.
3. The use of ice composite materials in the Arctic is a promising direction. Studies of the strength characteristics of KML with various types of reinforcement are actual and attractible, and this work will be continued.

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