Investigation of Ice Specimens Reinforced in the Middle Section with Thin-Walled Pipes Made of Polymeric Materials

A S Vasilyev1,a,b, V L Zemlyak1, V M Kozin1
1Sholom-Aleichem Primursky State University, 70, Shirokaya str., Birobidzhan, 679015, Russia

E-mail: a vasil-grunt@mail.ru, b vellkom@list.ru

Abstract. The paper is devoted to the construction of road crossings on the territory of the Arctic shelf and the Extreme North (Far North), as well as on the Siberian and Far Eastern rivers in winter. That is going to contribute to reducing logistic costs from cargo shipping down the ice surface significantly. In this research, the authors examine ice-based composites, where thin-walled polyvinyl chloride pipes are placed in the middle of the sample cross-section as a reinforcer. Two types of pipes were tested: vent white and orange sewer (drain) ones. While doing several series of model experiments, the researchers find out that the load-bearing capacity of ice samples reinforced with these pipes show very much the same results. So it was decided to combine the averaged model experiments with these pipes into one concluding result. The mechanical characteristics of ice were figured out by crushing samples of ice prisms that are 60 cm long, with a cross-section size of 15x15 cm. The aim of the paper is to define the influence of thin-walled polyvinylchloride pipes on the plastic properties and load-bearing capacity of ice samples when they are being reinforced. The test results prove that when reinforced with a pipe, it is destructed more gradually, and the deformations before the destruction have greater values. However, the thin-walled SN2 and SN4 pipes add nothing to increasing load-bearing capacity, unlike the SN8 sample, which increased the load-bearing capacity by about 10%. Therefore, the reinforced mid-section of ice samples with thin-walled PVC pipes marginally increased the plasticity of the samples, without the marked increase in the load-bearing capacity.

1. Introduction
In fact, bending-gravity/ground waves propagation are highly likely in the ice water synodic when a load moves at a particular (hump/critical) speed along the ice surface. The complete or partial ice failure is possible [1] at a certain rate.

In this regard, the problem of predicting and improving the plasticity and load-bearing capacity of ice, depending on its physical and mechanical properties, and the impact of moving loads on it becomes number one at present. In this paper, the authors deal with reinforcing ice with thin-walled polyvinyl chloride pipes and investigate their influence quantity on the strength and plastic properties of the ice-based composite material.

Many authors have been studying the destruction of the ice sheet and its mechanical characteristics. Kim H., Keune J.N. [2]; Lu, Wenjun, Lubbad, R., [3]; Renshaw, C.E.; Schulson, E.M.; Sigward, S.J.G. [4]; Tippmann, J.D.; Kim, H, Rhymer, J.D. [5]; Goldstein R. V, Osipenko N. M [6]; Vasilyev A.S. [7] investigated the ice failure due to normal, inclined and radial cracks in their studies.
A lot of works dedicated to the introduction of reinforcing elements in ice crossings. Yakimenko and Sirotyuk [8, 9, and 10] describe experimental research on the "surface reinforcement" of ice crossings with geosynthetic materials.

The studies of various authors [11-18] also inquire into the stress-strain behavior of ice. At present, the use of ice-based composites becomes a necessity. This is caused by several factors. It makes it possible to adjust the ice strength and plasticity, toughness and density, as well as the technical ability of the design. In this study, the ice samples were reinforced with polymeric materials: orange sewer pipes, as well as white vent pipes. Polymeric materials have some advantages: they are relatively cheap, have high chemical resistance, and are not corrotable. They also have a low density, which equals to a low weight, and consequently, do not reduce the available load when the ice crossing is reinforced. Sewer pipes are easy to freeze in ice due to their floatability. In this research, the authors have tested the extent to which polymeric thin-walled pipes of large diameter can change the mechanical properties of an ice-based composite material.

2. Materials

There are two types of sewer pipes: grey and orange. The main difference between them is that orange pipes are less sensitive to temperature fluctuations (variations), so they are more often used for laying external utilities, while grey pipes are used for running internal ones. This article is devoted to the ice samples reinforced with polymeric materials. Polyvinyl chloride pipes of two types are used for reinforcement. They are smooth (plain) orange sewer pipes and smooth white vent pipes. Orange pipes made of polyvinyl chloride (PVC) are intended for external sewer laying. According to the mechanical loading felt, such pipes are divided into three groups: SN2 are weaker, light, with a wall thickness of 2.3 mm, with load charge up to 2 kN; SN4 are mean strength and lightness, with a wall thickness of 2.5 mm to 12.3 mm, with load charge up to 4 kN; SN8 are the most durable, heavy, with a wall thickness of 3.2 to 15.3 mm, with load charge up to 8 kN.

Air flue pipes are white, with a wall thickness of 1.5 mm. They are classified by pressure resistibility in the following way: low ones are up to 900 Pa; medium ones are from 900 to 2000 Pa; high ones are over 2000 Pa. For these experiments, orange sewer pipes and white air flue pipes are used. Their diameter is 160 mm, wall thickness is 1.5 to 4 mm, with load charge up to 2 kN.

The value of the longitudinal (axis) stress is determined for pressure pipes as follows:

\[ \sigma_m = \frac{p \cdot R}{2 \cdot \delta} \]  

where \( p \) is a pipe pressure (in particular, the pressure for which these pipes are designed), \( R \) is the shell radius along the centre line, \( \delta \) is a shell thickness.

Figure 1. Sample cross-sections.
$$\sigma_{m, \text{white \_ pipe}} = \frac{2.0.08}{2.0.0015} = 53.3 \text{ kPa}$$

(2)

$$\sigma_{m, \text{orange \_ pipe}} = \frac{2.0.08}{2.0.004} = 20 \text{ kPa}$$

(3)

Geometric features of the pipes are shown in Figure 1. Here, the shaded area represents the ice, and the black elements stand for the section area of the pipes. Figure 1a shows a cross-section reinforced with a light orange SN2 sewer pipe. Figure 2 shows a cross-section of the sample reinforced with a white air flue pipe. 10 samples of each species were destroyed, then the values were averaged and a diagram was plotted. It should be noted that there was no big difference between the results of reinforcing the samples with a white and orange pipe, so these results will be combined into one.

3. Methods

3.1. Conducting simulated experiments

A universal installation was designed and developed [1] to perform model experiments to study the possibility of increasing the load-bearing capacity of the ice cover by introducing reinforcing elements into it. The walls and bottom of the formwork are made of boards with a thickness of 40 mm. The sidewalls and the bottom are connected by externally threaded spike grids. The end-type removable walls are hardened with steel angles and bolts. The presented formwork allows ice samples L×B×H=2000×200×200 mm in size to be prepared.

A double-layer polyethylene film was laid in the assembled formwork, then thin-walled pipes were placed at a given distance from the side planes. After that, water was poured. The liquid was affected to low atmospheric temperatures (t<0°C) until its extreme freezing. The sample preparation time, depending on the weather conditions was from 5 to 7 days at an ambient temperature of -16°C to -28°C.

![Figure 2. Breakdown test for a sample with an orange vent pipe.](image)

Figure 2 shows the breakdown test for a sample with an orange SN2 pipe. The crushing is at midspan as a result of the bending moment of flection, in the pure bending area.

4. Numerical model of ice destruction reinforced with plastic thin-walled pipes of wide diameter

The numerical investigation was performed in ANSYS PC. Ice was modeled by SOLID 65 finite elements based on the Willam-Warnke yield criterion [19, 20]. The pipes were modeled by SOLID 185 finite elements and looked like 3D thin-walled shapes. The efficiency of the model is confirmed by comparing the numerical calculation with the data of model experiments.

Ice characteristics: $$E_{\text{ice}}=0.5e3 \text{ MPa}$$, Poisson's ratio $$\mu_{\text{ice}}=0.3$$, compressive strength $$R_{b,\text{ice}}=0.25 \text{ MPa}$$, tensile strength $$R_{t,\text{ice}} = 0.2 \text{ MPa}$$. Characteristics of plastic thin-walled pipes: Young's modulus $$E_{\text{pipe}}=2e3 \text{ MPa}$$, Poisson's ratio $$\mu_{\text{pipe}}=0.4$$, tensile strength was calculated by the formula (1) and for the SN2 pipe was $$R_{\text{pipe}}=0.02 \text{ MPa}$$. For SN4 and SN8 pipes, respectively, 0.04 and 0.08 MPa.
Figure 3. Breakdown test results for SN8 sample: a–domestic cracking. b – normal pipe stresses.

Figure 3 shows that the pipe stresses are concentrated and reach higher values in places where there are cracks in the ice than in the general area of pure bending between the supporting structures.

5. Results

Table 2 show that the samples reinforced with thin-walled pipes can stand a larger time step value, and therefore, bear a heavy workload. For an unreinforced ice sample, a fast rise in normal stresses can be observed from 0.178 MPa in the previous step to 65 MPa in the 1.6 s. step, which corresponds to sudden brittle fracture. However, it is obvious that the ice samples reinforced with more durable pipes had lower stresses in the compressed zone at each loading step.

| Normal stresses in the compressed zone, mPa | Time step | 1.4 s. | 1.6 s. | 1.8 s. |
|---------------------------------------------|-----------|--------|--------|--------|
| Sample with orange pipe SN8                |           | -0.169 | -0.175 | -0.554 |
| Sample with orange pipe SN4                |           | -0.172 | -0.177 | -0.801 |
| Sample with orange pipe SN2                |           | 0.173  | 0.179  | 0.804  |
| Unreinforcement sample                      |           | 0.178  | 65     | -      |

Figure 4 shows the results of sample deflections with thin-walled pipes of various classes. Figure 5a shows that there is a good agreement between the computed data and the simulated experiment. It confirms the operational integrity of the model. The results of the deflection of the experiment and the calculation have an error of about 1%.

The results of the calculations of samples with pure bending in ANSYS PC are presented in Table 3. As the Table shows, an unreinforced sample has the largest deflection with the lowest load-bearing capacity. The sample reinforced with SN8 pipe normally shows the highest load-bearing capacity. The load-bearing capacity of this sample is 6.8% higher than that of the ice sample with no reinforcement.
| Experiment          | Deflection, mm | Breaking load, kg |
|---------------------|----------------|-------------------|
| SN2 Unreinforced    | 1.79           | 120               |
| Reinforced SN2      | 1.81           | 120               |
| Reinforced SN4      | 1.80           | 120               |
| Reinforced SN8      | 4              | 125               |

Table 2. Calculation results.

Figure 4. Results of sample deflections: a-comparison of experimental data and calculation, b-comparison of calculations of the unreinforced sample, as well as samples reinforced with pipes of different strength in ANSYS PC.

6. Conclusion
The calculations showed that the SN2 plastic tube did not significantly contribute to the increase in the load-bearing capacity or stiffness of the samples. Meanwhile, there is a good agreement of the calculated and experimental data when constructing the load-deflection diagram when comparing the data of the model experiment and the calculation for the samples reinforced with SN2.

The test findings proved that pipe reinforcement with proper strength values can increase both the ductility property of the samples and their load-bearing capacity. Nevertheless, the thin-walled SN2 and SN4 pipes did not contribute to the increase in load-bearing capacity greatly, opposed to the SN8 sample, which increased the load-bearing capacity by about 7%. Moreover, the plasticity increased by about 120%. To sum up, the reinforcement of the centre section of ice samples with thin-walled PVC pipes can increase both the plasticity and the load-bearing capacity of ice samples.

7. References
[1] Zemlyak V L, Kozin V M, Vasil’ev A S, Ipatov K I 2019 Experimental and Numerical Investigations of the Influence of Reinforcement on the Load-Carrying Capacity of Ice Crossings Soil Mechanics and Foundation Engineering 56 1 37-43
[2] Kim H, Keune J N 2007 Compressive strength of ice at impact strain rates Journal of Materials 42 8 2802-2806
3. Lu W J, Lubbad R, Loset S 2015 Out-of-plane failure of an ice floe: Radial-crack-initiation-controlled fracture Cold regions science and technology 119 183-203
4. Renshaw C E, Schulson E M 2017 SJG Sigward, Experimental observation of the onset of fracture percolation in columnar ice, Geophysical research letters 44 4 1795-1802
5. Tippmann J D, Kim H, Rhymer J D 2013 Experimentally validated strain rate dependent material model for spherical ice impact simulation International journal of impact engineering 57 43-54
6. Goldstein R V, Osipenko N M 2015 Some aspects of strength in sea ice mechanics Physical mesomechanics 18 2 139-148
7. Vasilyev A S, Zemlyak V L, Kozin V M 2020 Study of the physical and mechanical characteristics of the ice cover Materials Science Forum 974 482-487
8. Yakimenko O V, Sirotuyk V V 2014 Reinforcement of ice crossings Earth's Cryosphere 18 1 88-91
9. Yakimenko O V, Sirotuyk V V 2015 Strengthening of ice crossings by geosynthetic materials SibADI (Omsk)
10. Sirotuyk V V, Yakimenko O V, Levashov G M 2016 Reinforcement of ice cover with geosynthetics materials Earth's Cryosphere 20 3 86-94
11. Bychkovsky N N, Guryanov Y A 2005 Ice construction sites, roads and ferries Saratov State Technical University (Saratov)
12. Arkharov I A, Goncharova G Y 2010 Experimental analysis of ice structures modified by polymers Kholod. Tekh. 11 46-50
13. Goncharova G, Ustugova T, Nikiforova I, Razomasov N 2015 Experimental study of heat and mass transfer in modified ice structures resulted from diffusion of polymeric compounds used for sports ice objects Refrigeration Science and Technology 1099-1106
14. Buznik V M, Landik D N, Erasov V S, Nuzhnyi G A, Cherepanin R N, Novikov M M, Goncharova G Y, Razomasov N D, Razomasova T S, Ustyugova T G 2017 Physical and mechanical properties of composite materials on the basis of an ice matrix Inorganic Materials: Applied Research 8 4 618-625
15. Bai X, Zemlyak V, Vasilyev A, Kozin V 2020 Stressed-Deformed State of Ice Crossings at the Surface Reinforcement of Composite Materials Journal of Marine Science and Application 19 3 430-435
16. Cherepanin R N, Nuzhnyi G A, Razomasov N A, Goncharova G Y, Buznik V M 2018 Physicomechanical Properties of Glacial Composite Materials Reinforced by Rusar-S Fibers Inorganic Materials: Applied Research 9 1 114-120
17. Buznik V, Golushko S, Amelia E, Belyaev V, Bryndin L, Gorynin A, Shapeev V 2019 Determining the law of ice deformation Journal of Physics: Conference Series 1404 1 No 012010
18. Golushko S, Buznik V, Nuzhny G 2019 Mathematical modeling and numerical analysis of reinforced composite beams Journal of Physics: Conference Series 1268 1 No 012018
19. Willam K J, Warnke K J 1974 Constitutive model for the triaxial behavior of concrete Seminar of concrete structures subjected to triaxial stresses (Bergamo)
20. Bazant Z P, Cedolin L 1980 Fracture mechanics of reinforced concrete ASCE J Eng Mech Div. 106 6 1287-1306