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A REVIEW ON THE DEVELOPMENT OF THE METHODS OF ICE AND ICE-SOIL REINFORCEMENT

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ABSTRACT

The need to bring different building materials to the remote cold regions makes construction in these regions more difficult and rather expensive. The need to have such materials can be reduced by the use of both ice and ice-soil composites. This paper provides a description of various methods of reinforcement and creation of the composites of that kind. The classification of the various methods of ice(-soil) reinforcement and the results of studying the ice strengthened by disperse and fibrous reinforcement are presented. The analytical relationships for determining the strength of the ice reinforced with short length fibres are derived. Also the method of ice-soil reinforcement with cryotropic gel formation is described. The tests show that the shear strength and permeability properties of ice-soil composites created by the method of cryotropic gel formation are rather high even after thawing.

INTRODUCTION

In cold regions ice and ice soils or frozen soils are abundant and inexpensive to manufacture. The disadvantages of ice and frozen soils as construction materials are their relative weakness and creep behavior at temperatures close to $0^{o}C$. Their mechanical properties are strongly temperature-dependent, and melt protection is usually necessary even in the coldest areas of the world. To make ice more suitable and thus more applicable as an arctic construction material its strength must be increased and its tendency to creep must be diminished and for frozen soils their reduction of strength parameters at thawing should be decreased. Even in the coldest areas of the world the temperature of ice is so close to its melting temperature that its mechanical properties are strongly temperature-dependent. And melt protection is usually necessary. Freeze-thaw cycling is a weathering process which frequently occurs in cold regions. It has been found that the mechanical and thermo mechanical behavior of ice and ice soils can be improved by reinforcement. These methods of reinforcement or creations of ice and ice-soil composites are known since ancient times.

The inhabitance of northern regions traditionally used lichen to strengthen their igloos. During the Second World War in the Soviet Union for the vehicle descent on the ice of Ladoga lake on the "Life Road" during the siege of Leningrad different ways of ice reinforcement with the help of logs, branches and twigs were used. The reinforcement of river ice ferries with these materials was also used for heavy military transport in other areas of the Front (Bergman and Proskuryakov, 1943). The most amazing example of this was discovered in 1942 in an extensive and almost unique investigation of ice as a structural material. This was project Habakkuk which was a plan by the British in World War II to construct an aircraft carrier out of reinforced ice for use against German boats in the mid-Atlantic. It was supported by Winston Churchill and engaged leading scientists including J. D. Bernal and Max Perutz. The project was the brainchild of Geoffrey Pyke, an eccentric scientific adviser to Britain's war office. He proposed that aircraft carriers might be constructed cheaply from ice, which would be extremely resistant to explosives. This led to testing of the mechanics of ice beams in Canada in 1943, laying the foundations for much of the current understanding of ice as a material (Gold, 1989).

Ice is a special substance: it is plastic and ductile at low strain rates (that's why glaciers flow) but brittle at higher rates. Tests of how the strength of ice could be enhanced by additives such as cardboard, clay and cloth were carried out and the best material found was wood pulp. This conclusion was partly a result of a crack arrest in a manner similar to other composites such as ceramic composites; but Bernal pointed out that it could also be due to changes in the grain shape and size of ice, an effect known in metals. The composite was named "pykrete" - a mixture of ice and wood pulp. Since then a number of scientists have investigated reinforced ice.

At the peak of the Cold War there was again some interest in the methods of ice reinforcement. Runways for heavy-weight planes B-52 in the Arctic region have been built using the methods of reinforcement of ice by means of fiberglass (DeGoes and Neal, 1994).

Coble and Kingery (1963) looked at ice reinforced with wood products, fiberglass and asbestos. Dunaev (1957) investigated sea ice strengthened by hygroscopic agents (sawdust and slag), fresh water ice and algae. The properties of ice and snow reinforced with sawdust have been studied by Kagan et al. (1965) and Wuori (1963). Jarret and Biggar (1980) gave their recommendations on the use of geotechnical fabrics in ice, whilst Glockner (1988) suggested making fiber-reinforced ice domes. Nixon and Smith (1987) studied the toughness of wood-reinforced ice, and Kuehn and Nixon (1988) considered both toughness and bending strength of wood-reinforced ice, along with some simple economic aspects. Recently quite a lot of papers have been devoted to the research of reinforcement of ice (-soils) by geosynthetic materials (Haynes et al.,1992; Sirotyuk et al., 2008, 2009). All these scientists found that ice and ice soil could be effectively strengthened by reinforcement. However, the drawback of almost all of these reinforcing agents is they have to be transported to Arctic sites at a considerable cost. Therefore it is necessary to use local frozen soils more widely. Nowadays there is a growing interest in methods of cryotropic gel formation and the polymeric cryogels obtained by using these methods. The properties of the frozen soils (ice-soil composites) have to be improved for example in order to create reliable materials with a low filtration factor for building weirs and other hydrotechnical constructions, which operate under a wide range of temperatures, including positive temperatures (Altunina et al., 2006)

Therefore the methods of ice and ice-soil reinforcement were applicable not only in the past but they will be applicable in the future as it was suggested in the presentations made at the at *the Workshop on using in situ resources for construction of planetary*, for example to construct structures in deep space (Buehler, 1998).

THE METHODS OF ICE AND ICE-SOIL REINFORCEMENT

The methods of ice and ice-soil reinforcement with creation of ice and ice-soil composites can be divided into two types (Makkonen, 1994). The improvement of the strength of ice (soil) can be achieved in two main ways (see Figure 1):

- microscopic reinforcement
- macroscopic reinforcement.

Microscopic reinforcement

The first way to improve the strength parameters of ice (or ice as the weakest component of frozen soil) is to mix ice with a substance which will inhibit crack formation and propagation. This sort of reinforcement is mixed usually homogeneously and is called microscopic. A number of reinforcing materials have been proposed for microscopic reinforcement of ice and soil, including various water-soluble polymers, disperse and fibrous materials.

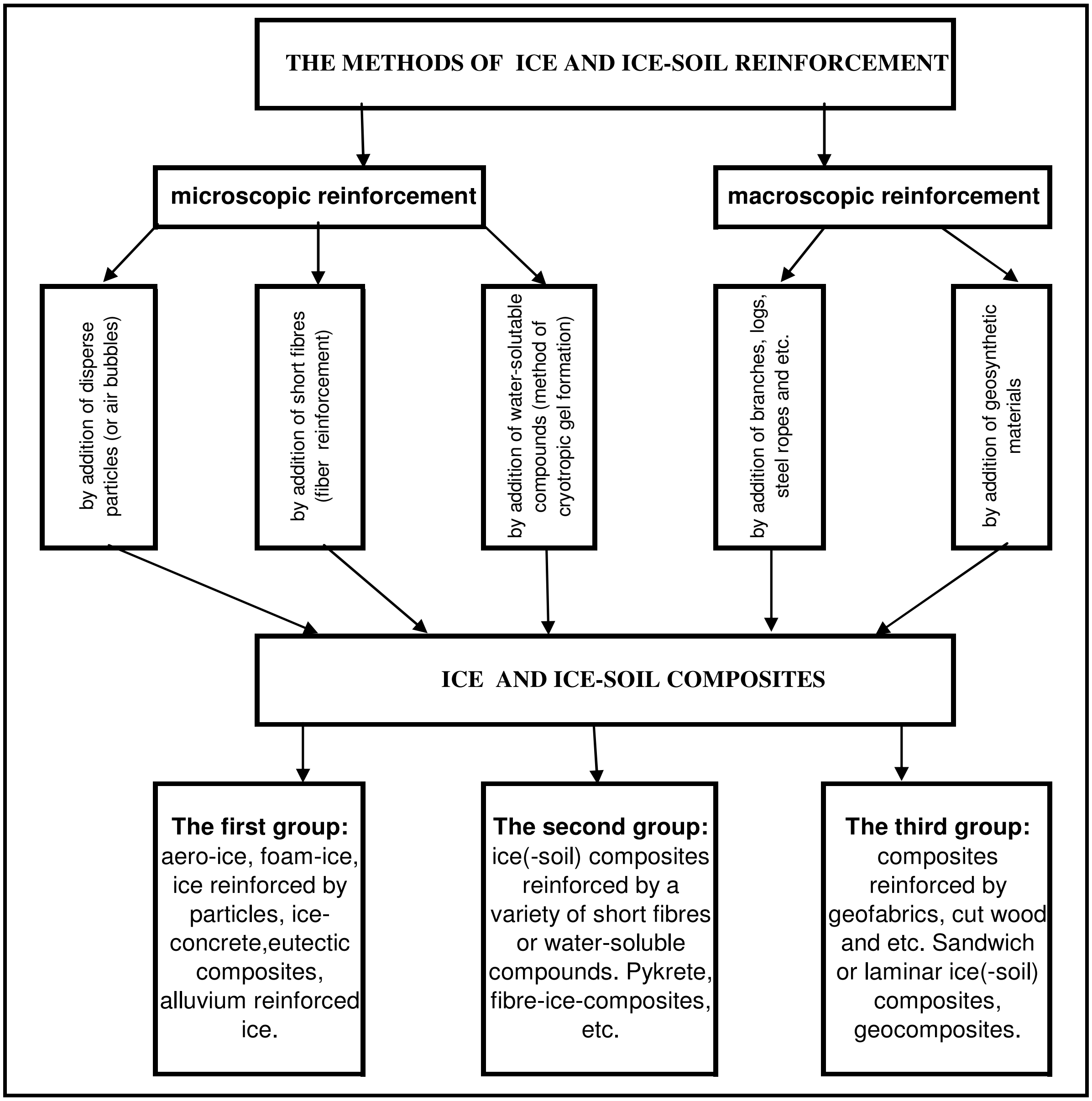

Figure 1. The methods of ice and ice-soil reinforcement.

The ice and soil composites obtained through microscopic reinforcement can be also divided into two groups:

1. The composites which consist of a continuous phase (ice) and a disperse phase (particles, pores, brine inclusions) - these are aerated ice or aeroice, foam-ice, ice composites with hard particles and frozen soils. Sea ice can be described as a composite of this group.

2. Ice and ice-soil composites with short fibers. Ice and ice-soil composites reinforced by a variety of wood-based materials (wood pulp, sawdust), glass fibers or water-soluble compounds.

The properties and the technology of the creation of the composites of the first group are described in (Vasiliev, 1994; Nixon, 1989; Kingery, 1960).

The methods of the creation of aero-ice and foam-ice are developed in (Smoryugin, 1988). The foam-ice is intended for the defense ice or ice construction from thermal influences. The weak strength of foam-ice while keeping its thermal resistance properties can be increased by method of cryotropic gel formation (Altunina et al., 2006; Vasiliev et al., 2009).

Tests (Nixon, 1989) show that ice can be strengthened significantly by the addition of alluvium: silica sands, gravels, coarse sands. The degree of strengthening has been proven to be dependent on both the type and the amount of alluvium. To increase the strength of ice up to 3 – 4 times it is better to use fine particles at more than 70% content. The similar results on reinforcement of ice with various disperse particles have been obtained earlier and are described in (Vasiliev, 1994). These results are presented in Figures 2a and 2b. The relative strength (*k*) or the strengthening coefficient is defined as a ratio of the strength of the reinforced ice to that of the unreinforced ice.

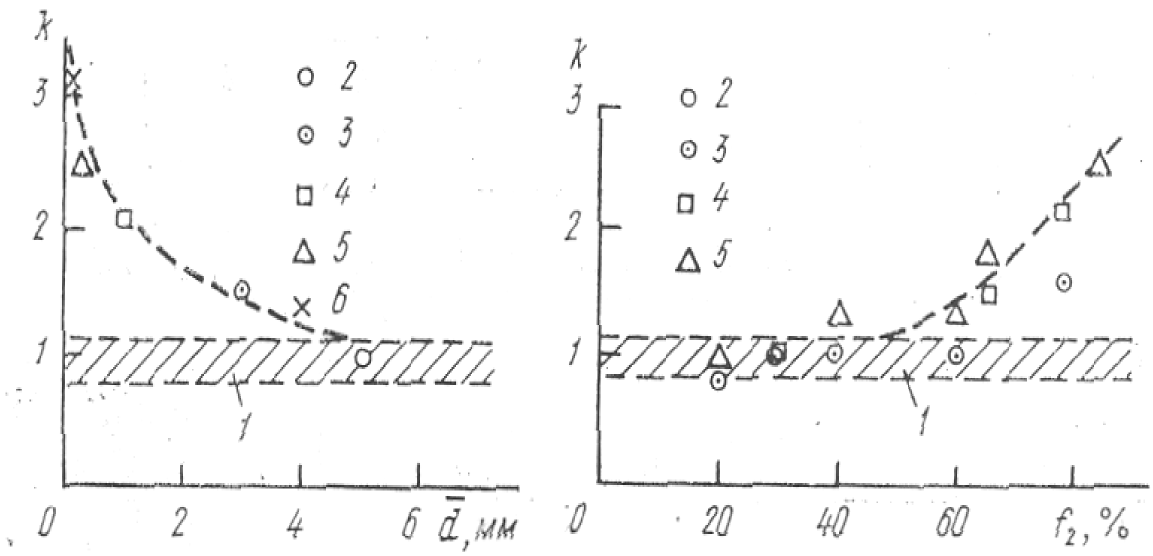

Figure 2a (picture on the left). Relative strength *k* at bending of ice composites with an average size of disperse particles of d, mm, and weight content particle f_2 ,% (temperature of the tests t = - 20 ^{o} C).
1 - "plain" ice; 2 – 6 - ice composites with particles of: 2 – claydite, f_2 =30; 3 – fine gravel, f_2 =74; 4 – coarse sand f_2 =78; 5 – fine sand, f_2 =80; 6 – clay particles, f_2 =72.

Figure 2b (picture on the right). Relative strength k at bending of ice composites with weight particle content f_2,% (temperature of the tests t = - 20 ^{o} C).
1 - "plain" ice; 2 – 5 - ice composites with particles of: 2 – claydite d=5mm; 3 – fine gravel, d=5mm; 4 – coarse sand d=1.1mm; 5 – fine sand, d=0.2mm.

The technology of creating ice-soil composites includes the following procedures: obtaining coarse grained frozen soil by blast-hole drilling (most common method), then grinding the soil with different types of machines and thawing the soil for further compaction. For example, the technology of a dam construction with local frozen soils placed into water is quite effective (Pechovich and Razgovorova, 1979).

This technology allows one to avoid labor intensive actions of thawing of the frozen soils, then arranging their storage and insulation. The advantage of this technology is the fact that the soils can be used in plastically-frozen conditions instead of thawing conditions.

As it was shown in the 1960s (Coble and Kingery, 1963) in the example of using starch for ice reinforcement it is possible to use water-soluble high-molecular compounds for this purpose. Some of these compounds have a number of features favorable for ice reinforcement such as solubility in water, ecological purity, low cost, reinforcing effect on such a brittle material as ice. Among other high-molecular compounds cryogels, PVA (polyvinyl alcohol) in the first place, are more effective for ice reinforcement (Vasiliev, 1988). PVA is a firm water-soluble polymer. It does not have any taste or smell, is nontoxic. Ecological cleanliness has been proven by the fact that the gels are used in medical purposes as cartilage tissue etc. (Lozinsky, 2002).

It has been shown (Vasiliev and et al., 2009) that ice-soils composites obtained by means of cryotropic gel formation on the basis of PVA retain the properties of solid body during thawing even after one cycle of freeze-thaw (see Figure 3). It has been proven by the performed tests in triaxial cells that the filtration factor of the ice-soil composites even after thawing is less than 10^{-5}-10^{-6} m/day. Also the tests performed in direct shear boxes showed that the shear strength parameters (internal friction and cohesion) of such cryogel soils have been improved in comparison with the same parameters of unreinforced soil under the same conditions. After thawing the ice-soil composites are extremely plastic at positive temperatures (see Figure 4). It is important in order to use them in watertight elements in dams. It is also known (Vasiliev, 1988) that at negative temperatures the samples of cryogel are more plastic than frozen ice. This is due to the fact that icy form of PVA solution is more plastic than normal ice.

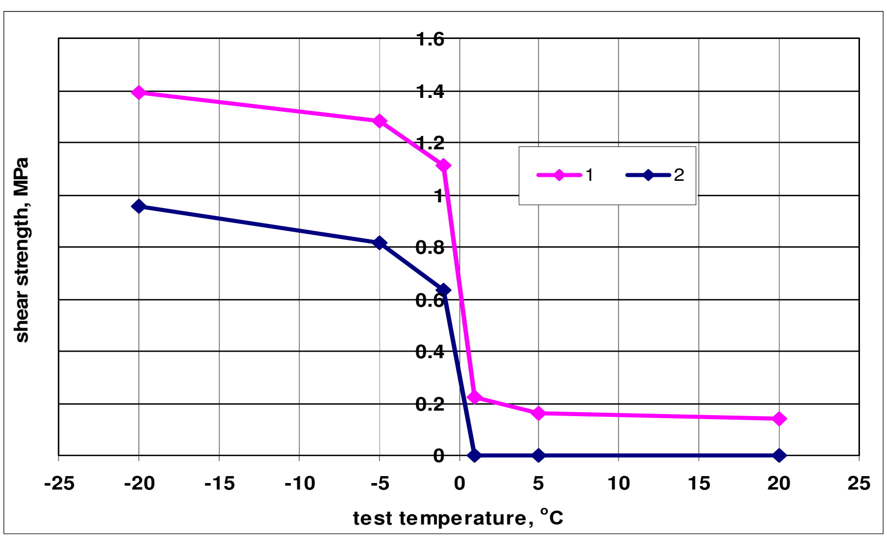

Figure 3. Shear strength of the soils versus test temperature during and after one cycle of freeze-thaw: 1- ice-soil composite obtained by means of cryotropic gel formation, 2 – control soil.

Figure 4. The view of cryogel samples after thawing before the bending force is applied (on the left picture) and during the application of the bending force (on the right picture).

The technology of strengthening of a frozen soil by means of method of cryotropic gel formation during construction of anti-filtration elements in weirs is protected by patents of the Russian Federation N 1600406 and N 2342484. The positive sides of the method are: high efficiency of erection of impermeable elements for both fresh and sea types of water. This high efficiency is explained by many advantages of cryotropic gels: the possibility of foam generating installations with ejectors and also by the fact that the formed elements are waterproof, nontoxic, flexible (in the wet conditions they are capable of “selfcuring” the cracks), dissolvable in water and are very strong. Cryogels can be prepared in situ and injected into soils using standart equipment. Also it has been noticed that the more cycles of freezing-thawing in which cryogel participates there have been, the greater cohesion and the friction angle of the soils are.

The developed methods of cryotropic gel formation are promising, for example for the creation of impermeable barriers at hydrosystems in the cold regions. The cryotropic gels were successfully applied during the pilot tests when sealing a leaking interval at the base of a dam at the Irelyakh hydrosystem (Altunina et al., 2006).

Fibrous materials have proven (Coble and Kingery, 1963) to be one of the most effective strengtheners of ice.

The strength of ice reinforced with elastic fibers and subjected to long term loading can be calculated with the use of the law of mixtures. According to this law it is apparent that ice or ice-soil can be strengthened significantly by fibrous materials with high strength and elastic modulus. Also the fiber length should exceed the critical length (l_c), given by (Lim et al., 1987):

$$l_c = \sigma_2 d / 2 \tau \quad (1)$$

where σ_2 is the reinforcing fiber strength; d is the fiber diameter; τ is the ultimate interfacial bond stress. For ice relationship of the fiberglass yarn critical length (l_c) to test temperature is defined in the work of Vasiliev (1993).

Typical load-deflection curve for fiber ice composites in the flexure is given in Figure 5. An important observation of Figure 5 is that the initiation of the failure is not catastrophic and is different from the failure of "plain" ice or ice composites of the first group. The curve is linear up to the point A, which is commonly defined as the first crack stress. Further loading leads to a non–linear curve represented by the curve AB. At ultimate load a simultaneous matrix cracking and composite fracture occur, but sudden failure of the specimen is prevented due to the resistance of fibers during the pull-out (the curve BC).

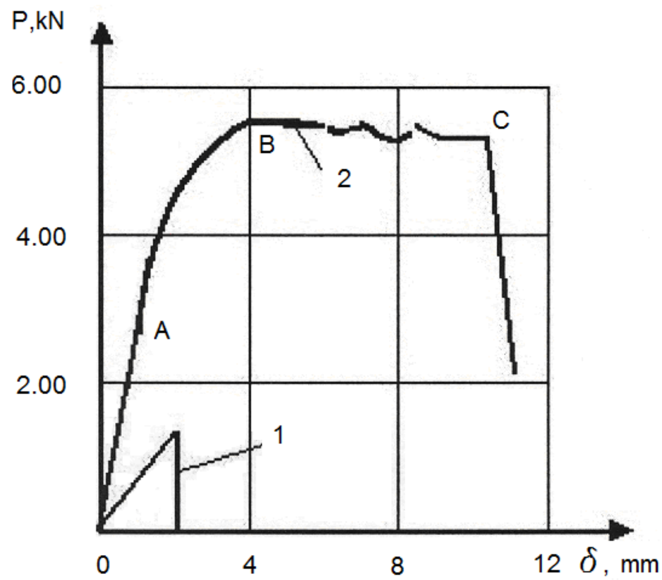

Figure 5. Typical load-deflection curve for "plain" ice (1) and for fiber ice composites (2).

The post-ultimate load capacity of the composites can be significant. Ultimate strength (σ_c) of the composite in the flexure may be defined (Mangat and Gurusamy, 1987):

$$\sigma_c = A\, \sigma_1\, (1 - \Phi_2) + B\, \Phi_2\, l/d \qquad (2)$$

where A, B – the empirical constants: A = 0.6 – 1.0; B = 2.4 $\beta\tau$, β – the coefficient indicating the fibre distribution and orientation , τ – the ultimate interfacial bond stress between ice and fibre, σ_1 – the strength of the matrix, Φ_2 – the volumetric content of reinforcing materials, l/d - ratio of length to diameter of fiber.

The analytical relationships for determining the ultimate strength (σ_c) in flexure of ice composites reinforced with short fibers have been derived in the work of Vasiliev and Gladkov (2003). For the fiberglass ice composites (with l <25 mm):

$$\sigma_c = 1.4\,(1 + 0.07\,|\,t\,|) + 0.29\,(|\,t\,|)^{0.63}\ \Phi_2\, l/d \qquad (3)$$

for the ice composites reinforced by sawdust (with l <10 mm)

$$\sigma_c = 1.4\,(1 + 0.07\,|t|) + 0.36\,(|t|)^{0.63}\,\Phi_2\,l/d \qquad (4)$$

where σ_c is the ultimate strength of composite in flexure in MPa, $|t|$ is the absolute value of the temperature of the test in ^{o}C.

It has been proven that high tendency to creep of ice considerably decreases when the fibers are added (Kingery, 1960; Cederwall, 1981). Also, fracture strength of the ice composites with short fibers in comparison with the "plain" ice is higher (Nixon and Smith, 1987).

Many investigators have conducted various (triaxial, compression, direct shear, etc.) strength tests on soil reinforced with paper, nylon, metal, and polymers fibers (Guang-Xin Li et al., 2008). In the cold climates, soil is exposed to freeze-thaw cycles which are important in cold region engineering. Qi et al. (2006) reviewed the last efforts made to investigate the influence of freeze-thaw cycles on soil properties. According to this research generally these cycles reduce the ultimate strength of soils. From this point of view the method of cryotropic gel formation considered above is quite promising as it was shown that (Vasiliev et al., 2009) the properties of ice-soil composites during freeze-thaw cycles do not get worse but even improve.

Macroscopic reinforcement

The second way of reinforcement can be named macroscopic as it suggests using of continuous materials: nets, tree trunks, steel, and geogrid. In this case these composites consist of two or more continuous phases – sandwich or laminar types of composites.

A number of studies have been conducted to examine the effects of macro-reinforcement on the bearing strength of ice and soil. A lot of field tests have been performed and documented by Fransson (1983) in which cut wood and steal bars were used as reinforcement. These materials were generally placed onto the top part of the ice sheet. Even though the reinforcement was not optimally placed, Fransson and Elfgren (1986) noted that sawn wood provided good reinforcement, while birch branches provided no discernible reinforcing effect. Twigs proved to provide the lowest effect as a reinforcement material in comparison with sawdust. The results of the tests illustrating this are shown in the Table 1 (Yakovenko, 1985).

Table 1. Ice reinforcement with wooden materials.

weight content of wood additives, %	Relative strength *k*			
	Compression tests		Shear tests	
	Samples with sawdust	Samples with twigs	Samples with sawdust	Samples with twigs
2	1.4	1.00	1.00	0.80
5	1.68	1.05	1.20	0.87
7	2.09	1.20	1.20	0.90
10	2.39	1.30	1.23	0.95

Nowadays there is a growing interest in the methods of reinforcement of both ice and soil with geomaterials. From the bearing capacity tests for ice sheet, geogrid increased the maximum load-carrying capability of 30-mm ice up to 300%, of 49-mm ice up to 38%, of 65-mm ice up to 13 of 65-mm ice up to 13%. The tests (Sirotyuk et al., 2008) show that the maximum value of ice sheet bearing capacity is reached with using of fiber glass net.

These kinds of reinforcement methods which combine the advantages of different approaches to create high-strength and thermo stable ice (-soil) composites, which stay solid after thawing are very promising for application in cold regions.

CONCLUSIONS

In spite of the accelerating development of the methods of ice and ice-soil reinforcement the application of them is limited. On one hand despite of a lot of papers devoted to this problem a more detailed and systematic knowledge of strengthenig mechanism of reinforced ice and ice-soil would obviously allow for a better design of reinforced ice for a particular field of application. On the other hand it is also necessary to develop procedures of using the methods in practice.

These methods can be effectively applied in many spheres (e.g. designing and buidling of hydrotechnical and transport river and sea structures).

The choice of the type of an ice (-soil) composite is determined by the technical and economic assessment which takes into account the costs of the creation of the ice (-soil) composite (the equipment and the material delivery etc.) and the technical economic effect which is received as a result of using this type of solution: reduction of the construction period, increase of the construction reliability and elongation of the time the structure constructed can be used.

Furthermore, in terms of cost, the use of locally available materials such as ice and frozen soil would result in the reduction of the cost of construction.

REFERENCES

Altunina, L.K., Kuvshinov, V.A., Dolgikh, S.N., 2006. Cryogels – Promising Material for Underground Works in Permafrost. In: Lombardi, S., Altunina, L.K., Beaubien, S.E. ed. Advances in Geological Storage of Carbon Dioxide. NATO Science Series. IV. Earth and Enviromental Sciences. Springer. V. 65, pp. 103-110.

Altunina, L.K., Mangai, V.N., Fufaeva, V.C., 2006. Mechanical and Thermophysical Properties of Cryogels and Foamcryogels, Obtained from PVA Water Solution. Journal of Prikladnoi Khimii. V.79. N10, pp. 1689-1693 (In Russian).

Bergman, G.R. and Proskuryakov, B. V. ed., 1943. Ice ferries. Moscow, Sverdlovsk: Gidrometeoizdat (in Russian).

Buehler, D., 1998. Obtaining and Utilizing Extraterrestrial Water. Workshop on ISRU Construction. LPI Technical Report 98-01, pp. 3-4.

Cederwall, K., 1981. Behaviour of a Reinforced Ice Cover with Regard to Creep. In: Proceedings of International Conference on Port and Ocean Engeneering under Arctic Conditions (POAC), Quebec, Vol.1, pp. 562-570.

Coble, R. L. and Kingery, W. D., 1963. Ice reinforcement. In: Kingery, W. D. ed. Ice and Snow. M. I. T. Press, Cambridge, MA. Ch.12.

DeGoes Louis, Neal, J. T., 1998. Selected Military Geology Programs in the Arctic, 1950-1970. Reviews in Engineering Geology. Geological society of America XIII, pp.205-211

Dunaev, E. S., 1957. Sea Water Ice as a Construction Material. Proc. D. V. P. I., 46 (11), pp. 1-26 (in Russian).

Fransson, L., 1983. Full Scale Tests of the Bearing Capacity of an Ice Sheet. In: Proceedings of International Conference on Port and Ocean Engeneering under Arctic Conditions (POAC'83), Helsinki, Vol.2., pp.687-697.

Fransson, L., Elfgren, L., 1986. Field Investigation of Load-curvature Characteristics of Reinforced Ice, in Proceedings of POLARTECH 86 Conference, VTT, Helsinki, vol.1, pp. 175-196.

Glockner, P. G., 1988. Reinforced Ice and Ice Domes: Opportunities for the North. Int. J. Space Struct., 3 (2), pp. 84-102.

Gold, L.W., 1989. The Habbakuk Project – Building Ship from Ice. In: Proceedings of International Conference on Port and Ocean Engeneering under Arctic Conditions (POAC'89), Lulea, Vol.1, pp.1211-1228.

Guang-Xin Li, Yun-Min Chen, Xiao-Wu Tang. 2008. Geosynthetics in Civil and Environmental Engineering. Springer.

Haynes, F. D., Collins, C. M., Olson, W.W., 1992. Bearing Capacity of Ice Reinforced with Geogrid. Special report 92-28/ US Army Corps of Engineers, Philadelphia.

Jarret, P. M. and Biggar, K. W., 1980. Ice Reinforcement with Geotechnical Fabrics. NRC Canada, Assoc. Commun. Geotechnical Resources, Tech Memo. No. 129, pp. 60-68.

Kagan, G. L., Peschansky, I. S., Shvaushtein, Z. I. and Nazintsev, U. L., 1965. The investigation of New Wood Fibre Ice Material. Proc. Conf. Hydrotech., 23, pp. 23-33 (in Russian).

Kingery, W.D., 1960. Applied Glaciology - the Utilization of Ice and Snow in Arctic Operations. J. Glaciol., 3 (27), pp. 577-588.

Kuehn, G. A. and Nixon, W. A.,1988. Reinforced ice: Mechanical properties and cost analysis for its use in platforms and roads. Proc. 7th Int. OMAE Symp. 4, pp. 193-200.

Lozinsky, V.I., 2002. Cryogels on the Basis of Natural and Synthetic Polymers: Production, Properties and Domains of Application (Криогели на основе природных и синтетических полимеров: получение, свойства и области применения). Uspekhi Khimii, Vol. 71, pp. 559 – 585 (in Russian).

Lim, T.Y., Paramasivam, P. and Lee, S.L., 1987. Bending Behaviour of Steel-fiber Concrete Beams. ACI Struct. J., 84 (6), pp. 524-536.

Makkonen, L. ed., 1994. Ice and Construction. RILEM Technical Committee TC-118.

Mangat, S., Gurusamy, K., 1987. Flexural Strength of Steel Fibre-reinforced Cement Composites. J. of Material Sci., 22. pp. 3103-3110.

Nixon, W. A. and Smith, R. A., 1987. The fracture toughness of some wood-ice composites. Cold Reg. Sci. Technol.. 14 (2), pp. 139-145.

Nixon, W.A., 1989. Alluvium-reinforced ice: A Preliminary Report of Bending Strength Tests. Cold Reg. Sci. and Technol., 16, pp. 309-313.

Pechovich, A. I., Razgovorova, E. L.,1979. Investigation of Frozen Soil Compaction after Placing Them into Water. Izvestiya VNIIG , vol. 130, pp. 92-99 (in Russian).

Qi J.L. et al. 2006. A Review of the Influence of Freze-Thaw Cycles on Soil Geotechnical Properties. Permafrost and Periglac. Process.17, pp. 245-252.

Smoryugin, G. I., 1988. Theory and Methods of Creations of Artificial Ice. Novosibirsk: Nauka (in Russian).

Sirotyuk, V.V. et al., 2008. Building and Testing of an Ice Bridge Reinforced with Geogrid. Vestnik TGASU, 4, pp. 157-165. (in Russian).

Sirotyuk, V.V. et al., 2009. Use of Geosynthetic Materials for Reinforcement of Winter Roads and Ice Ferries. Avtomobilnye Dorogi. № 11 (936), pp. 64-67. (in Russian).

Vasiliev, N.K., 1988. The Research on Strengthening of Ice Using Water-Soluble High-Molecular Substances. Izvestiya of the B.E. Vedeneev VNIIG, Vol. 205, pp. 45- 48 (in Russian).

Vasiliev, N.K., Shatalina, I.N., Razgovorova, E.L., Portnyagin, L.G., Sidorov, M.P., The B. E. Vedeneev VNIIG, Inc. 1990. Method of the Erection of a Soil Weir of a Frozen Type. Patent of the Russian Federation N 1600406.

Vasiliev, N.K., et al., The B. E. Vedeneev VNIIG, Inc.. 1991. Method of Creation of Reinforced Ice-snow Cover. Patent of the Russian Federation N 1715920.

Vasiliev, N.K., 1993. On Development of Fibre-ice-composites. Cold Reg. Sci. and Technol., 21, pp. 195-199.

Vasiliev N.K., 1994. Ice Composites: Properties and Technology of Creation. Izvestiya of the B.E. Vedeneev VNIIG, 228, pp. 28-36 (in Russian).

Vasiliev, N.K., Gladkov M.G., 2003. Ice Composites: Mechanical Properties and Methods of Creation. In Proceedings of the 17th International Conference on Port and Ocean Engeneering under Arctic Conditions (POAC'03), Trondheim, vol.1, pp.119-127.

Vasiliev, N.K., Sokurov, V.V., Ivanov, A.A., Shatalina, I.N., Razgovorova, E.L., The B. E. Vedeneev VNIIG, Inc. 2008. Method of Creation of a Water-resistant Screen in the Soil Materials of the Elements of a Hydrotechnical Structure. Patent of the Russian Federation N 2342484.

Vasiliev, N.K. et al., 2009. Strengthening Frozen Soils Using the Method of Cryotropic Gel Formation. In Proceedings of International Conference on Port and Ocean Engeneering under Arctic Conditions (POAC'09), Lulea.

Wuori, A. F.,1963. Snow Stabilization Studies. Ice and Snow. Cambridge, MA: M. I. T. Press.

Yakovenko, V.G., 1985. About Reinforcement of Ice with Wooden Additions. SevNIP, Arkhangelsk.