



ICE COMPOSITES AS CONSTRUCTION MATERIALS IN PROJECTS OF ICE STRUCTURES

N. K. Vasiliev¹, A.D.C. Pronk²

¹ PhD, Soil Mechanics Laboratory, The B.E. Vedenev VNIIG Inc., St Petersburg, Russia,
nicolaivasiliev@hotmail.com

² Assistant Professor, Faculty Architecture, Building & Planning, University of Technology,
Eindhoven, Netherlands, *a.d.c.pronk@tue.nl*

ABSTRACT

It is known the application of ice as a building material has some limitations. Ice is a relatively weak material and shows an extreme creep behavior compared to conventional building materials. Mechanical properties of ice are strongly temperature-dependent and anti-melt protection is necessary even in the coldest areas. It has been found that the properties of ice and sea ice can be improved by reinforcement by forming these ice composites.

The classification of the various methods of ice reinforcement is presented. In spite of many papers about ice reinforcement ice composites have very limited application. An overview of all existing construction methods, which involve ice structures, is provided in the paper. At present time only three types of ice composite such as pykrete (pykrete is a frozen composite material made of the mix of sawdust or some other form of wood pulp and water or sea water), cryogel ice-soil composite and ice reinforced by geomaterials, have been applied successfully in engineering of structure in the various projects.

A brief information about these projects is presented. The description of the projects called the 'Pykrete Dome' and the 'Sagrada Familia in Ice' are expanded. The projects have been carried out in Finland in 2014 and 2015. The 'Pykrete Dome' has been the largest ice dome ever constructed in the world and the 'Sagrada Familia in Ice' – the highest pykrete construction.

INTRODUCTION

It is known ice composites can apply successfully in engineering structures. In spite of a lot of research works about ice composites in this century at present time there are only three examples of reinforced ice structures: (i) ice roads on ice cover of sea gulf, rivers and lakes – ice ferries reinforced by geomaterials, (ii) watertight elements in the dam of Irelyakh hydro system in Siberia and (iii) ice dome on an inflatable mould constructed in the winters of 2014 - 2015 in Finland. We have only few examples because there is a gap between the use of reinforcement and the building methods. The aim of this paper is to research efforts to fill the gap. The authors show that there is a need to stimulate the development of a building method for ice composites.

HISTORICAL ASPECTS

Engineering structures from ice composites are known since ancient times. The first and most famous building is of course the igloo. The development of building ice structure is presented in the Table 1.

Table 1. Some historical events

Nº	Time	Reinforced material or method	Structure	The place
1	Ancient times	Lichen	Igloo	The northern regions of Canada, USA and Russia (Eskimos, Chukchi)
2	During the Second World War	Logs, branches and twigs	Ice road and ice ferries	Ladoga Lake 'Life Road" USSR (Ice ferries,1943) Ice railway bridge over the Dnieper (Ukraine, winter 1941-1942
3		Wood pulp (pykrete)	Aircraft carrier	Project Habakkuk, Canada, Great Britain,1942-1943. (Gold,1989)
4	During the Cold War	Fiberglass	Ice airstrip	Arctic region, USA,1966. (DeGoes, Neal, 1998)
5		Sawdust (pykrete)	Ice roads crossing swamps	Siberian region, USSR, 1960-1968. (Borshchuk, 1968)
6		Wooden covering	Ice working space	Siberian region, rivers, USSR,1966. (Marchuk,1973)
7	Nowadays	Geonets from fiberglass	Ice roads crossing rivers	Arkhangelsk region, Russia (2010-2012)www.ador.ru/data/files/does/in novations_01.pdf
8		The method of cryotropic gel formation	Watertight elements in dams	Irelyah hydrosystem, Siberia, Russia,2005. (Altunina et al., 2010)
9		Pykrete	Ice Dome, Sagrada Familia in Ice	Juuka, Finland, 2014 (Pronk, 2014) Nunnanlahti,Juuka, Finland, 2015

METHODS OF ICE REINFORCEMENT FOR ICE STRUCTURES

The methods of ice and ice-soil reinforcement with creation of ice and ice-soil composites can be divided into two types (Ice and Construction, 1994): microscopic and macroscopic reinforcement. Microscopic reinforcement may be applied for all types of ice engineering structures, while macroscopic reinforcement is mainly used for foundations of roads and ferries. The first way to improve the strength parameters of ice (or as a component of frozen soil or soil as a complex system) is to mix ice with a substance which will inhibit crack formation and propagation. This sort of reinforcement is usually mixed homogeneously and is called microscopic.

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 type 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 and his colleagues (Fransson and Elfgrén, 1986).

A number of reinforcing materials have been proposed for reinforcement of ice and ice-soil, including various water-soluble polymers, disperse and fibrous materials is shown in Table 2.

Table 2. The information about reinforcing materials for ice composites and research works

[illegible]

REINFORCED ICE STRUCTURES

To the date there are only three examples of reinforced ice structures: ice ferries reinforced by geomaterials, watertight elements in the dam of Irelyakh hydro system in Siberia and the Pykrete Dome on an inflatable mould realized in the winter of 2014 in Finland.

1. 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., 2009) show that the maximum value of ice sheet bearing capacity is reached with using of fiber glass net.

During 2011 the field tests were conducted in Arhangelsk region of Russia by MIAKOM Ltd. It was built the reinforced (with fiberglass net with mesh 50x50mm) ice road crossed river Peza that allowed to prolong the operation period more than 20 days (http://miakoming.ru/InfoTech/Ledovie_perepravy). Now it may have high potential use the geomaterials on ice road in cold regions and in the regions where have thin or cracked ice.

2. In recent years a great deal of attention has been focused on the study of cryogels obtained by the methods of cryotropic gel formation (Lozinsky, 2014). Cryogels are considered as potential materials for solving practical problems. Especially it concerns cryogels with a polyvinyl alcohol base. The material created by using the method is called the cryogel ice soil composite. From the information contained in the research work (Vasiliev and Ivanov, 2013) the developed cryogel ice soil composites have low water permeability for building watertight elements of dams and other hydro engineering constructions, which operate under a wide range of temperatures, including positive temperatures.

There are three ways for creating water tight elements:

- injection,
- bore piling,
- deep mixing.

The injection was used to seal a leaking interval at the base of Irelyakh hydrosystem dam (Altunina et al., 2010). The 51 tons of aqueous solutions of polyvinyl alcohol with additives were pumped into the five holes made in the cold base ground dam. The following check tests show the used injection at the Irelyakh hydrosystem was successful.

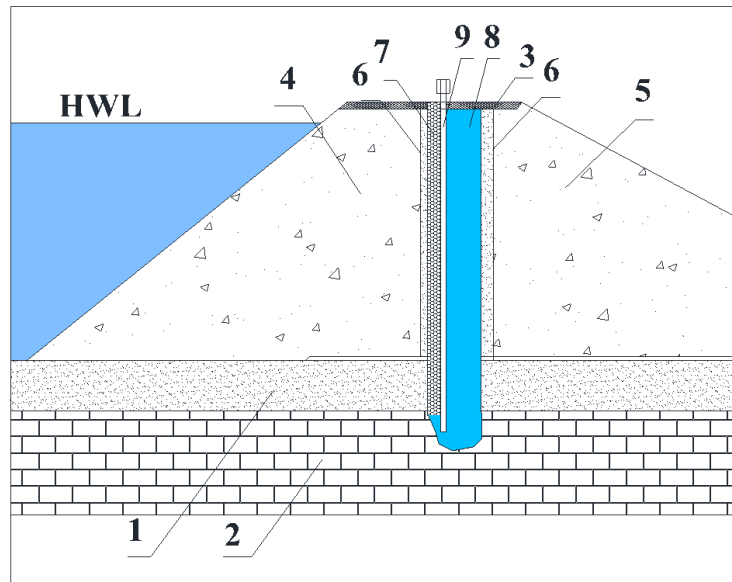


Figure 1. Water retaining and heat-isolating construction for dams of frozen type.

1 – thawing permeable layer; 2 – permafrost soil; 3 – heat-insulating cryogel composite layer 4 – upstream rubble-mound dam shell; 5 - downstream rubble-mound dam shell; 6 – sand protection zone; 7 – water retaining and heat-isolating cryogel soil composite diaphragm; 8 – frozen curtain; 9 – seasonal freezing columns. HWL – head water level.

In Figure 1 an example of water retaining and heat-isolating construction for dams of frozen type is shown. In the case using another ways of retaining wall construction employ deep mixing or bored piling techniques. The composition of the developed cryogel soil composite and its technology of using for the construction of water-retaining elements in dams of frozen type is protected by patents of the Russian Federation (Vasiliev et al, 1993, 2008). The material presents a wide range of advantages, such as its good regulated characteristics including high plasticity and impermeability.

3. From the time of Second World War until the building of the pykrete dome in this year no large-scale structures have been built with reinforced ice – pykrete. Pykrete has some interesting properties, notably its relatively slow melting rate (because of low thermal conductivity), and its vastly improved strength and toughness over ice; it is closer in form to concrete.

Pykrete is a frozen composite material made of approximately 14 percent sawdust and 86 percent ice by weight. Its use was proposed during World War II by Geoffrey Pyke to the British Royal Navy as a candidate material for making a huge, unsinkable aircraft carrier (Gold, 1989).

Only a few examples of structures built with the use of pykrete are available. In recent years it is known the ice arch made by civil engineering students of the Fairbanks University, Alaska and the 30 meter span Pykrete Dome in Juuka, Finland, build by scientists and students from Eindhoven University of Technology (Pronk et al., 2014a). The final Pykrete Dome design is a result of a combination of various studies. The research on ice shells by T. Kokawa provide a simple and efficient construction method. The construction method is analysed and improved for an optimal design of the pykrete dome. The relative weak and brittle construction material – ice. Ice is reinforced and replaced with a stronger ductile material pykrete. The method of creating pykrete by spraying is developed and used. The sawdust added to the mixture created a more complex processable material. Previous experimental research by A. Pronk, F. Janssen and R. Houben (Janssen and Houben, 2013) showed that slush (mixture of snow, water and sawdust) caused problems with the compressible behavior of the snow. The snow was compressed under the high pressure of the pump, resulting in an ice formation in the pump or at the end of the hose at the nozzle. Therefore the spraying of water was separated from the adjustment of snow on the inflatable mould like in the construction method of T. Kokawa. Different from the method of Kokawa, sawdust was added to the water. A slush of water with sawdust was sprayed into thin layers of snow on the surface of the inflatable mould.

Ten percent of sawdust appeared to provide the best values for both mechanical and processing behavior. This optimized behavior concerns the homogeneousness, the processability, the toughness and strength of the pykrete. The particles of the sawdust have to be small (up to a maximum of 2 mm). When the sawdust is saturated, it becomes heavier than water and sinks to the bottom. To maintain the homogeneous behavior of the mixture, the sawdust should be prevented from sinking. When using pumps to process the pykrete mixture and retain the homogeneous aspects, extra attention should be paid to the size and type of the pump. The small particle size of sawdust creates a better processability. Bigger particles can stop a pump immediately. The compressive strength of pykrete with 10% sawdust can be 12 MPa and the flexural strength can be 3.7 MPa. Compared to regular ice 3 MPa and 1.2 MPa this is 3 times better. The ductility of pykrete is even 10 times better. With the improved toughness, the pykrete allows a higher deformation of the structure and reduces crack formations. Pykrete also improves the resistance against thermo shock that might occur during the building process as a result of the spraying of water on the frozen shell structure.

The ‘Pykrete Dome’ was made during 3 weeks by a team of 50 people. The Pykrete Dome became the first realized project in which pykrete was on such a scale. The view of the

dome presented on the Figure 2. The calculation and construction of the Pykrete Dome are described in (Pronk et al., 2014b). The shape of the 'Pykrete Dome' is spherical, the internal dimensions are measured with a laser device. Span is 29060 mm, height-9750 mm. It was 20 meter bigger than the previous official [Guinness book] largest ice dome in the world and 5 meters bigger than the unofficial record by T. Kokawa in Japan. To make this size possible, the 'Pykrete Dome' was partly constructed with pykrete. A slush of water with sawdust was sprayed into thin layers of snow on the surface of the inflatable (Figure 3).

In 2015 a consortium of scientists from Eindhoven University of Technology in close cooperation with other research institutes and the local community of Juuka (Finland) have build a 1:5 scale model of the Sagrada Familia in Ice - the world highest ice dome of pykrete with a height of 30 meters (Figure 4).

The Design of the 'Sagrada Familia in Ice' is based on the design of the real Sagrada Familia by Antoni Gaudí. The Sagrada Familia is designed by a model with suspended chains, which is better known as catenary design. A suspended chain or rope will always get the shape of a smooth curve, meaning that the chain is only subjected to tension and absolutely no pressure. If the curve of the chain is turned upside down it means the shape is only subjected to pressure and absolutely no tension. The principle of catenary design can be very interesting when building with ice, because ice has very low tensile strength. The design of the 'Sagrada Familia in Ice' consists of the big tower with a height of 30m, the nave with a height of 12m and the four towers of 21m (2x) and 18m (2x). Full details of the constructions made with pykrete are given in *www.structuralice.com*.

CONCLUSIONS

An increasing number of papers devoted to the methods of ice and ice-soil reinforcement attests to the accelerating of their development. On the one hand a more detailed and systemic knowledge of strengthening mechanism of reinforced ice and ice-soil is available. On the other hand the application of them is still limited. Therefore practical usage of these results is to be introduced next.

The advantages of using different techniques of reinforcement should be proven by not only theoretical comparison with conventional methods, using multiple factor analysis, but also by introducing a number of successful middle-scale experiments, similar to the one by A. Pronk, which may open the way of using cheap and attractive materials in practice.



Figure 2. The 'Pykrete Dome' (photo by TU/e, Bart van Overbeeke).



Figure 3. The spraying of pykrete (photo by TU/e, Bart van Overbeeke).



Figure 4. The 'Sagrada Familia in Ice' (photo by N.K. Vasiliev).

REFERENCES

- Abele, G., 1964. Some properties of sawdust-snow-ice mixtures. US Army Cold Regions Research and Engineering Laboratory. Special Report. SR-60. -12p.
- Altunina, L.K., Kuvshinov, V.A., Dolgikh, S.N., 2010. Cryogels for plugging in cold and permafrost regions. *Gidrotehnika*. 3, 52-57(in Russian).
- Bastian, J., 2010. The mechanical properties of select formulations of pykrete augmented emulsifier in uniaxial compression. ENGR 059 December 13,2010 http://andeanbastian.com/pykrete/ENGR_059_frinal_report.pdf
- Borshchuk, I. L., (1968). Methods of improvement of ice and snow properties at temperature about 0 °C. Science Information of the USSR Geographic Society. Baikal Department, Chita.9, 72-90 (in Russian).
- Cederwall, K., 1981. Behaviour of a reinforced ice cover with regard to creep. In *Proceedings of International Conference on Port and Ocean Engineering under Arctic Conditions (POAC)*, Quebec, Canada, Vol.1, 562-570.
- Coble, R. L. and Kingery, W. D., 1963. Ice reinforcement. In: W. D. Kingery (Editor), *Ice and Snow*. M. I. T. Press, Cambridge, MA. Ch.12.
- DeGoes, L. and Neal, J. T., 1998. Selected Military Geology Programs in the Arctic, 1950-1970. *Reviews in Engineering Geology*. Geological society of America XIII, 205-211.

Dunaev, E. S., 1957. Sea water ice as a construction material. Proc. D. V. P. I., 46 (11), 1-26 (in Russian).

Fransson, L. and Elfgren, L., Field investigation of load-curvature characteristics of reinforced ice, in Proceedings of POLARTECH 86 Conference, VTT, Helsinki, 1986, vol.1, 175-196.

Glockner, P. G., 1988. Reinforced ice and ice domes: opportunities for the North. Int. J. Space Struct., 3 (2), 84-102.

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

Grabe, G., 1986. Reinforced ice as a construction material-creep of reinforced ice. Proceedings of POLARTECH, 86. Vol.2, 793-806.

Ice and Construction / Edited by L. Makkonen. 1994. RILEM Technical Committee TC-118 -97p
Ice ferries/ Editors: G. R. Bregman and B. V. Proskuryakov, 1943. M., Sverdlovsk. Gidrometeoizdat (in Russian).

Janssen, F.H.M.E. and Houben, R.W.G., 2013. Reinforced ice structures. Eindhoven University of Technology.-262 p.

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.

Jia Hui Li, Zhen Wei, Chao Wu, 2015. Preparations and properties of novel building materials at low temperature. Materials and Design., vol.67, 15, 464-468.

Kagan, G. L., Peschansky, I. S., Shvaushtein, Z. I. , Nazintsev, U. L., 1965. The investigation of new wood fibre ice material. Proc. Conf. Hydrotech., 23, 23-33 (in Russian).

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, 193-200.

Lozinsky, V.I., 2014. Brief history of polymeric cryogels. Advance in Polymer Science.v.263, 1-48.

Marchuk, A.N. Damming under ice cover. M. Energia.-103 p. (in Russian)

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

Nixon, W.A., 1989. Alluvium-reinforced ice: A preliminary report of bending strength tests. Cold Reg. Sci. and Technol., 16, 309-313.

- Pronk, A.D.C., Vasiliev, N.K., Janssen, F.H.M.E., Houben, R.W.G., 2014a. Spraying pykrete. The spraying of water and wood fibers to reinforce ice. Proceedings of the IASS-SLTE 2014 Symposium "Shells, Membranes and Spatial Structures:Footprints",Brasilia, Brazil.
- Pronk, A.D.C., Borgart, A., Hijl, J.M., Pluijmen, R.M.F., 2014b. The calculation and construction of a 30 meter span ice dome. Proceedings of the IASS-SLTE 2014 Symposium "Shells, Membranes and Spatial Structures:Footprints",Brasilia, Brazil.
- Sirotyuk, V.V., et al., 2009. Use of geosynthetic materials for reinforcement of winter roads and ice ferries. *Avtomobilnue Dorogi*. 11, (936), 64-67 (in Russian).
- Stanley, R. G., Glockner P. G., 1976. Some Properties of Reinforced Ice Department of Civil Engineering. University of Calgary, Calgary, Alberta, Canada. -20p.
- Vasiliev, N.K., 1993. On development of fibre-ice-composites. *Cold Reg. Sci.and Technol.*, 21, 195-199.
- Vasiliev, N.K. et al., 1993. Patent of the Russian Federation N 1796650. Compound for an artificial ice (in Russian).
- Vasiliev, N.K. and Gladkov, M.G., 2003. Ice composites: Mechanical Properties and Methods of Creation. In Proceedings of the 17th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'03), Trondheim, Norway, vol.1, 119-127.
- Vasiliev, N.K. et al., 2008. Patent of the Russian Federation N 2342484. Method of Creation of a Water-resistant Screen in the Soil Materials of the Elements of a Hydrotechnical Structure (in Russian).
- Vasiliev, N.K., Ivanov, A.A., Sokurov, V.V., Shatalina, I. N., Vasilyev, K. N. 2011. A Review On Development Of The Methods Of Ice and Ice-Soil Reinforcement. The 21th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC 11, 2011, Montreal, Canada. www.poac.com
- Vasiliev, N.K., Ivanov, A.A., Sokurov, V.V., Shatalina, I.N., Vasilyev, K.N. 2012. Strength properties of ice-soil composites created by method of cryotropic gel formation. *Cold Reg. Sci. and Technol.*, vol. 70, 94-97.
- Vasiliev, N.K. and Ivanov A.A. 2013. Watertight ice and cryogel-soil composite membranes in upper parts of dams consructed in cold regions. Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, POAC 13, 2013. Espoo, Finland. www.poac.com
- Wuori, A. F.,1963. Snow stabilization studies. In: W. D. Kingery (Editor), *Ice and Snow*. M. I. T. Press, Cambridge, MA.