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Use of reinforced ice as alternative building material in cold regions: an overview

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Abstract The design of suitable thermophysical properties of reinforced ice as well as employing the novel material in feasible ways represent key aspects towards alternative building sustainability. In this overview research studies dealing with reinforced ice structures have been presented with an emphasis on construction parameters and reinforcement materials of the structures. The main focus of the study is directed to the identification of the main issues related to the construction of reinforced ice structures as well as the environmental and economic impact of such structures. Obtained research data shows that the compressive, tensile, and bending strength of reinforced ice can be increased up to 6 times compared to plain ice. The application of reinforcement materials decreases creep rate, enhances ductility, and reduces brittle behaviour of ice. Assessed reinforced ice structures were mainly found to be environmentally friendly and economically viable. However, in most of the analysed studies construction parameters and physical properties were not defined precisely. The conducted overview indicates the necessity for more comprehensive and more accurate data regarding reinforced ice construction, applied methods, and processes, and preparation of ice composites in general.

Keywords: Ice structures; Reinforced ice; Ice composite

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1 Introduction

With growing concerns over carbon dioxide pollution, ways are being sought to reduce the emissions. Innovative abundant earth materials could play a significant role in that challenge. In 2009 the global construction sector generated 5.7 billion tons of carbon dioxide, both from energy use and cement production [1]. That equals to 23% carbon dioxide emissions from global economic activities [1]. In cold areas construction is very costly and time consuming, as transportation of building materials to cold remote regions is a difficult and expensive process [2]. Hence, it is of great importance for cryogenic environments to consider the use of indigenous natural materials, like ice and frozen soil, as well as the latest developments and techniques in producing novel materials [3]. With water being the most common compound on Earth, renewable, abundant, and clean, it has a strong potential of being used in sustainable, clean technologies. It is crucial to have reliable data on thermophysical properties of ice and frozen soil in order to widen their application in cryogenic environments. Frozen soil effects on concrete have been examined in [4] but there is still space to broaden the investigations of ice.

Structures made of ice are known since ancient times when people were building ice shelters to protect themselves from cold weather. Nonetheless, it has been stated that there is still insufficient understanding of ice as a material [5]. Ice has a couple of downsides when compared to conventional engineering materials: it is brittle, relatively weak, and prone to creep behaviour [6]. Because of its natural origin, it is not as homogeneous nor workable as conventional building materials. However, ice can become much more applicable with the use of reinforcement. First known structure made from reinforced ice was an igloo – a combination of ice, snow, and lichen [6], after which no progress was made until World War II when reinforced ice has started to be utilized for building bridges and roads for military purposes. Bridge over Dnieper River in Ukraine and ice roads on Ladoga Lake in Russia were made of ice reinforced with logs, branches, and twigs [6]. At the time project Habakkuk took place – it was a plan to construct an aircraft carrier out of ice strengthened with wood pulp (pykrete) [7]. Although the project never came to life, it gave rise to the research of possibilities and applications of ice reinforcement. During Cold War, project Ice Way was conducted in Greenland with a goal to make an airstrip out of sea ice strengthened with fibreglass. Ice was treated as a readily available and inexhaustible local construction material [8]. Ice domes were first made at the University of Calgary, Canada. Unlike igloos, no blocks were used but a thin-walled structure was created by spraying water on an inflatable formwork with a network of fibreglass yarn [3]. Since then, ice domes and similarly shaped structures have been made in the cryogenic environments around the globe, as a part of winter festivals and experimental projects, like pykrete dome [9], and Sagrada Familia [10], in Juuka, Finland, Candela pavilion in Ghent, Belgium [11], Flamenco Ice Tower, ice pavilion THRICE [12], and Koi-fish ice shell in Harbin, China [13], all made of ice reinforced with some type of cellulose fibres. In 2019 first restaurant made of paper-reinforced ice was built in Harbin, China [14]. Ice roads crossing rivers in Arkhangelsk region in Russia have been reinforced with geonets from fibreglass [15]. Reinforced ice has been used in the form of cryogels to seal a leakage at the base of a dame at the Russian Irelyakh hydro system [16]. Reinforced ice as a sustainable and often fully recyclable building material could be used for all kinds of temporary constructions in cold areas, ice events, the Winter Olympics and even Mars missions [9].

Research demonstrated that there is a wide range of possibilities for ice reinforcement and the reinforcement methods are constantly developing and progressing [6]. However, applications of reinforced ice were not covered well and nor were the problems arising from the processes of producing ice composites and building the structures.

The main objective of this work is focused on those aspects and offers an encompassing study of achievable applications considering the construction parameters (method of construction, wall thickness, cooling method) and reinforcement method (material, mass fraction, particle size). Although numerous studies have dealt with reinforced ice, possibilities of reinforcement and properties of ice composites, not many have used reinforced ice in practice. In this work only ice composites that have been put in practice have been presented along with building techniques and issues that appeared in the process. The economic and environmental aspects of the novel materials have also been discussed. Hence, the analysis of herein presented reinforced ice structures provides a useful basis for comparisons and problems identification.

1.1 Review methodology

Reviewed articles were obtained mainly from Elsevier's Scopus database. According to the Elsevier's Scopus database and based on targeted keywords, research work done in the area from 1988 until today has been very modest with a total of 41 publications, including articles and conference papers, dealing with reinforced ice and ice composites, Fig. 1 [17].

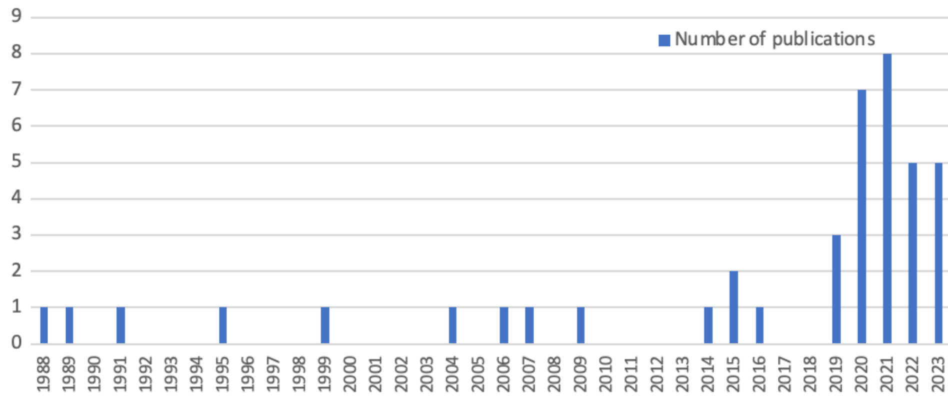


Figure 1: Number of publications dealing with reinforced ice through the years [17].

However, a rise in the number of publications can be observed from the year 2019 onwards. Specifically, from 2019 until today the sum of 28 publications was released which is almost 70% of a total number of publications associated with ice reinforcement possibilities and applications. It is a clear indicator that the interest of the research community for reinforced ice, although still low, is on the rise. Most of the research studies related to the investigation of ice were done in the fields of engineering and material science which suggests the interest in the usage of reinforced ice for engineering purposes.

The selection process consisted of two stages. The primary selection was made with respect to the targeted keywords. The subject area was limited to engineering, material science, earth and planetary sciences and environmental science. Document type was chosen to be papers only and written in English. Time range was not taken because overall a limited number of research papers are related to the herein considered search topic. In the second step, papers focused on ice reinforcement and those that cover reinforced ice structures were selected.

The aim of this work is to introduce and compare the possibilities of using reinforced ice as a building material. Thus, an overview of different reinforced ice structures is given with emphasis on construction parameters and environmental and economic aspects of the structures.

2 Comparison of thermophysical properties of pure ice and reinforced ice

2.1 Thermophysical properties of pure ice

Ice has many crystal structures, but in nature it can be found in 12 crystalline and 2 amorphous forms [18]. Under standard conditions (0°C, 101 325 Pa), it has a hexagonal crystal lattice (I_h). Ice is less dense than water with a density of 916.4 kg m^{-3} at 0°C, and the value increases as the temperature decreases [18].

2.1.1 Thermal properties of pure ice

In Table 1 thermal properties of pure ice (I_h) at −20°C [18] and 0°C [19] are presented. It is apparent that the thermal conductivity of ice is about 4 times greater than that of water and increases with the decrease of temperature. On the contrary, the specific heat of ice decreases with temperature decreasing and it is more than two times lower than the specific heat of the water [20].

Table 1: Thermal properties of pure ice (I_h) at −20°C [18] and 0°C [19].

Property	Symbol	Unit	Value	
			−20°C	0°C
Thermal conductivity	λ	Wm^{-1}K^{-1}	2.4	2.2
Specific heat capacity	c	kJkg^{-1}K	1.96	2.01
Latent heat of fusion	r	kJkg^{-1}	333.5	334
Linear expansion coefficient	α	K^{-1}	5.3×10^{-5}	10^{-6}

Measured thermal conductivities of pure ice found in literature depend largely on specific chemical composition of water used, and the temperature of ice specimens. Most notable conducted measurements were summarized by Fukusako [21], Fig. 2. Variations between the values is due to the fact that each researcher used different preparation methods and different ways to collect the experimental data.

Latent heat of fusion of ice represents a change in enthalpy as a unit mass of ice coverts into water isothermally and reversibly [21]. Measured values showed that the latent heat of fusion for ice at 0°C under atmospheric pressure is 333.9 kJkg^{-1} and decreases with temperature decreasing [21].

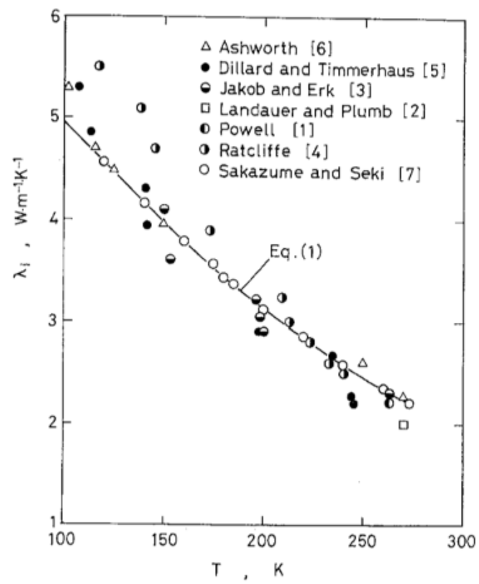


Figure 2: Thermal conductivity of pure ice in the range from $-173.15°$C to approx. $0°$C [21].

Linear thermal expansion coefficient is a fractional change in length per one kelvin change in temperature. It increases with the temperature increase, as well as coefficient of cubic expansion of ice, Fig. 3. Yen gave an adequate

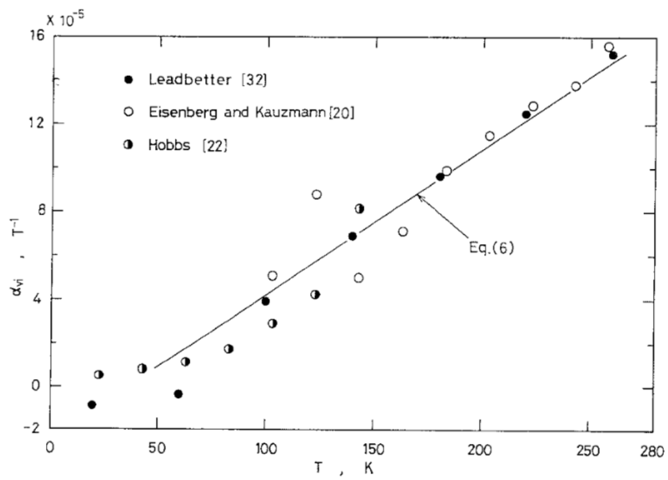


Figure 3: Cubic expansion coefficient as a function of temperature [21].

expression to calculate cubic expansion of ice [22]:

$$\alpha_{vi} = (0.67\,T - 24.86) \times 10^{-6}, \tag{1}$$

where T is the temperature in K.

2.1.2 Elastic properties of pure ice

When compared to conventional building materials, ice is more of an insulator than a conductor [19]. Main elastic properties of I_h are shown in Table 2 [19]. Ice can be observed quite isotropic elastically but is meaningly anisotropic plastically [18]. Its noteworthy mechanical properties are elasticity, viscoelasticity, viscoplasticity, creep rupture, and brittle failure [18]. Both ductile and brittle behaviour is noticeable when dealing with ice. Ice behaves ductile at low strain rates, but when the strain increases it becomes exceptionally brittle [20]. Aside from it demonstrating brittle and creep behaviour, it is also distinctly weak when compared to conventional building materials [6]. Ice strength has shown to be dependent on temperature, freezing process, presence of impurities, structure, chemical composition, load, application rate, etc. [2]. Shear and tensile strength of pure ice have almost identical values while compressive strength is nearly 3 times greater than the latter [2]. The compressive strength of the meteoritic ice demonstrates a notable decrease in temperature, from a maximum of $\sim$ 40 MPa at -50°C to a minimum of $\sim$ 3 MPa at 0°C. The tensile strength of the meteoritic ice is an order of magnitude lower than the compressive strength (between $\sim$ 1 and 3 MPa) and exhibits an insignificant temperature dependence in comparison. Empirical data insinuates that ice is less rigid than many widespread materials such as glass [20]. As stated by the parameter provided by code GB 51202-2016 [23], the linear expansion coefficient of

Table 2: Elastic properties of pure ice (I_h) [19].

Property	Symbol	Unit	Value
Young's modulus	E	Nm^{-2}	9.33×10^9
Compressibility	K	m^2N^{-1}	112.4×10^{-12}
Bulk modulus	B	Nm^{-2}	8.9×10^9
Shear modulus	G	Nm^{-2}	3.52×10^9
Poisson's ratio	n	–	0.325

ice is approximately 50×10^{-6}°C, meaning 5 times higher than that of the concrete [23].

2.2 Thermophysical properties of reinforced ice and comparison with pure ice

Reinforced ice has been examined mostly mechanically, whilst its thermal properties remain unknown. Only data available in literature are measurements made on pykrete, whose thermal conductivity and diffusivity were examined and subsequently compared to the measured values for pure ice [24]. Values of thermal conductivity were shown to vary between 1.637 $\mathrm{Wm^{-1}K^{-1}}$ at −15°C to 1.749 $\mathrm{Wm^{-1}K^{-1}}$ at −33°C what is calculated to be approx. 21% lower than values measured for pure ice with the same technique [24]. When it comes to thermal diffusivity, measured data ranged from 0.877 $\mathrm{mm^2s^{-1}}$ at −15°C to 1.107 $\mathrm{mm^2s^{-1}}$ at −33°C, showing a drop of approx. 23% when compared with values obtained for pure ice with same method [24].

When considering the overall properties of reinforced ice, more than a few advantages over plain ice can be identified. The reinforcement makes ice more deformable and can decelerate the creep rate [6]. Adding reinforcement can shorten the freezing time which is a major financial advantage when significant amounts of water need to be frozen. Compared to pure ice, reinforced ice is less affected by thermal shock [5]. Obtained experimental data shows that the use of different kinds of reinforcement can provide a significant improvement in the mechanical properties of ice. It has been investigated that the compressive strength of ice reinforced with pulp fibres can reach up to 3 times that of the plain ice [6]. Conducted research shows that introduction of fillers like basalt fibres leads to an increase in tensile strength by a factor of 2–3 [25], and an increase in bending strength by 1.5 times [2]. Even better results were obtained by Buznik *et al.* [26], who reinforced pure ice both chemically with dopants, and physically with basalt rovings and showed an increase in the strength properties of the reinforced ice specimens by 4-6 times compared to freshwater ice samples. Still, the most approved ice composite is a mixture of ice and some forms of wood pulp, such as wood chips, shavings, and sawdust, known as pykrete, Fig. 4.

Pykrete displays a low thermal conductivity which decreases ice melting rate. Its ductility has shown to be 10 times higher than of the plain ice [6]. Several authors have examined the mechanical properties of the

Figure 4: Pykrete samples [9].

pykrete, varying the type of wood pulp and the percentage used. According to Vasiliev *et al.*, the best mechanical properties were accomplished with pykrete reinforced with 10% sawdust [6]. In comparison to plain ice up to 4 times higher compressive and flexural strength was attained with the values of 12 MPa, Fig. 5, and 3.7 MPa, Fig. 6, respectively.

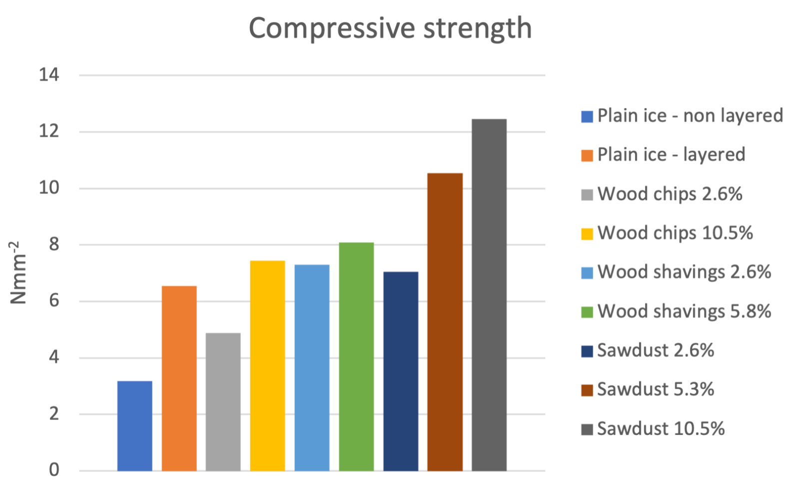


Figure 5: Compressive strength of plain ice and pykrete samples [6].

Pykrete bending tests, Fig. 7, were carried out by the group of students to check mechanical properties of specimens with different fibre percentage. The results have shown plentiful dissipation, i.e., the average compressive strength measured on specimens with 10.5% of fibres was in the range from 3.74 MPa on prisms to 12.45 MPa on cubic specimens [10]. Cryogel composites have shown to be capable of resolving issues in the freezing-thawing

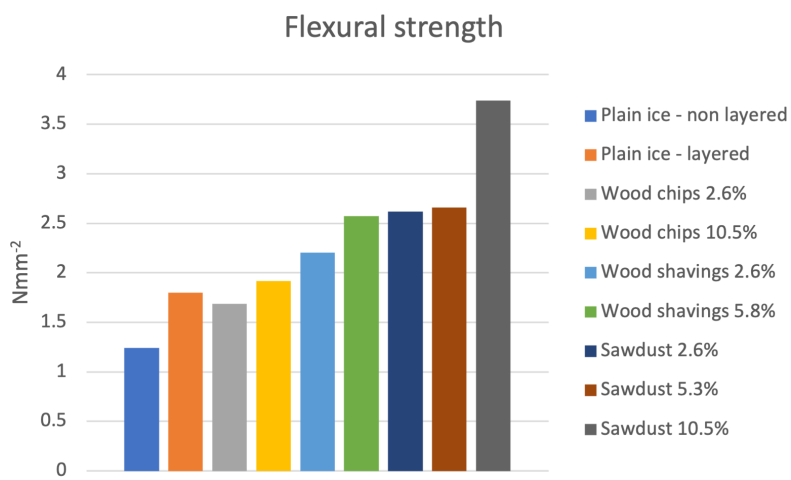
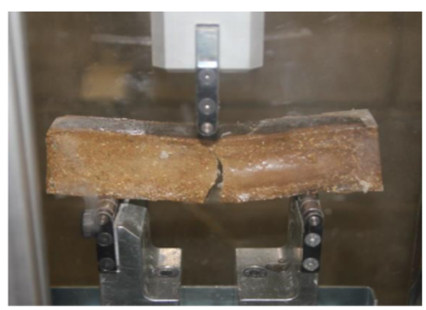


Figure 6: Flexural strength of plain ice and pykrete samples [6].

contact zones that occur in the hydraulic engineering and transport structures [6]. Prior to being used as watertight elements, cryogel solutions made with polyvinyl alcohol (PVA) were examined in the laboratory experiments as described in [16]. It was observed that subsequent freezing-thawing cycles improve the strength of cryogels.

(a)

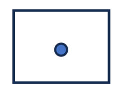
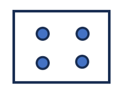


(b)

Figure 7: Sample casting (a) and bending test (b) on pykrete specimen [10].

Also, modulus of elasticity can be increased by increasing the concentration of polyvinyl alcohol and cross-linking agent, as well as the by adding electrolyte. The properties of ice reinforced with spun fibreglass yarn were first investigated in late 20th century [3]. Shear strength tests were executed by Glockner [3] on specimens with different quantities of yarn strands. It was observed that all specimens failed by brittle failure after 3–5 s at stress levels between 2.2 MPa and 2.7 MPa, Table 3.

Table 3: Results of sheer strength tests for ice reinforced with spun fiberglass yarn [3].

Number of strands of fiberglass yarn	Failure stress, MPa	Average failure stress, MPa	Placement of yarn in cross-section
0	2.59 2.61 2.25 2.35	2.45	
1	2.45 2.48 2.55 2.44	2.48	
4	2.70 2.29	2.49	

Therefore, the spun fibreglass did not improve the shear strength of ice when subjected to short duration loads. The author stated that it was expected as fibreglass itself has no shear strength. Short load-duration elastic tests were also carried out by varying amounts and forms of spun fibreglass yarn reinforcement. Failure of specimens happened 3–4 s after the loading started. While in plain ice the initial cracking stress was also the ultimate, it was not the case with reinforced ice, Fig. 8.

The average initial tensile cracking stress for the reinforced specimens turned out to be about 25% larger than the corresponding stress for plain ice specimens, 1.82 MPa and 2.33 MPa, respectively. That indicated that reinforcement prevents crack initiation and propagation, thereby increasing the tensile strength. In the long-term (creep) tensile strength test, both plain and reinforced ice specimens exhibited a typical creep deformation curve with failure taking place towards the end of decelerating creep stage. At the stress of 1.02 MPa unreinforced specimens crept to failure whilst reinforced specimen continued to creep at a steady rate until the load was removed. When the stress rate was reduced to 0.68 MPa plain ice specimens continued to creep without failure. Consequently, it was concluded that between 0.68 MPa and 1.02 MPa there is a critical stress level below which plain ice does not creep to failure. More details about the size, structure, and preparation of the samples can be found in the paper by Glockner [3]. Based on the results of the tests carried out by Vasiliev and Gladkov [9],

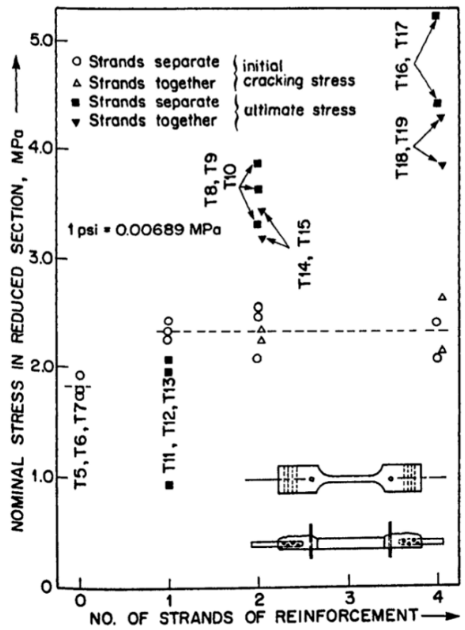


Figure 8: Tensile test results of fibreglass reinforced ice [3].

Table 4, it can be concluded that ice reinforced with fibreglass shows a significant increase both in compression and flexural strength, and a slight increase in dynamic elastic modulus. Ice with 4% fibreglass cloth has shown better properties in all categories than ice with 2% fibreglass net. All test materials have shown an increase in strength as the temperature decreased.

Table 4: Mechanical properties of reinforced ice examined by Vasiliev and Gladkov [9].

Test material*	Temperature, °C	Dynamic elastic modulus, GPa	Compression strength, MPa	Relative compression strength	Flexural strength, MPa	Relative flexural strength
Plain ice	–5	7.0	1.5	1.0	1.8	1.0
	0	8.0	2.5	1.0	2.5	1.0
Ice with 2% fibreglass net	–5	8.0	2.9	2.0	5.1	2.9
	–20	8.8	5.0	2.0	8.5	3.4
Ice with 4% fibreglass cloth	–5	8.2	3.2	2.1	5.2	3.0
	–20	9.2	6.0	2.4	10.0	4.0

*Ice specimens reinforced with fibreglass net or cloth uniformly distributed through the thickness of the ice.

By changing its temperature, differences in the mechanical properties of ice occur. At temperatures close to 0°C, ice has shown ductile and creep behaviour. The crystal structure, stress level, impurities, size of grains and temperature have an influence on creep behaviour. Creep behaviour was analysed by Kokawa [27], where in ice shell construction, linear increase of creep deflection was spotted at the beginning (stationary stage), but as time progresses the deflection rate accelerate until collapse, Fig. 9.

(a) (b)

Figure 9: (a) Creep deformation just before the collapse [27]. (b) Model of creep deflection-time curve [27]: $\delta(\varepsilon)$ – creep deflection (mm/day), t – time (day), ε – uniaxial strain rate, f – complete failure, m – end of stationary stage.

Plain ice properties can be considerably improved by using suitable reinforcement. The percentage and the type of the reinforcement material directly influence the thermophysical and the mechanical properties of the composite [5]. When compared to conventional building materials, a lack of uniformity of pure ice can be noticed which leads to the inability to manage and anticipate its behaviour. By developing a systematic and formal knowledge of the ways and mechanisms of the reinforcement and the properties of reinforced ice, many ambiguities concerning ice behaviour could be diminished. Appropriate reinforcement used comprehensively in the construction of reinforced ice structures has yet to be established and/or embraced.

3 Possibilities of using reinforced ice as a building material

There are only two design codes for ice and snow structures that can be found: the first one is the Finland snow construction – general rules for design and construction [28], and the other is Chinese Technical standard for ice and snow landscape buildings [23]. Ice reinforcement can be divided into two categories: macroscopic and microscopic reinforcement, Fig. 10.

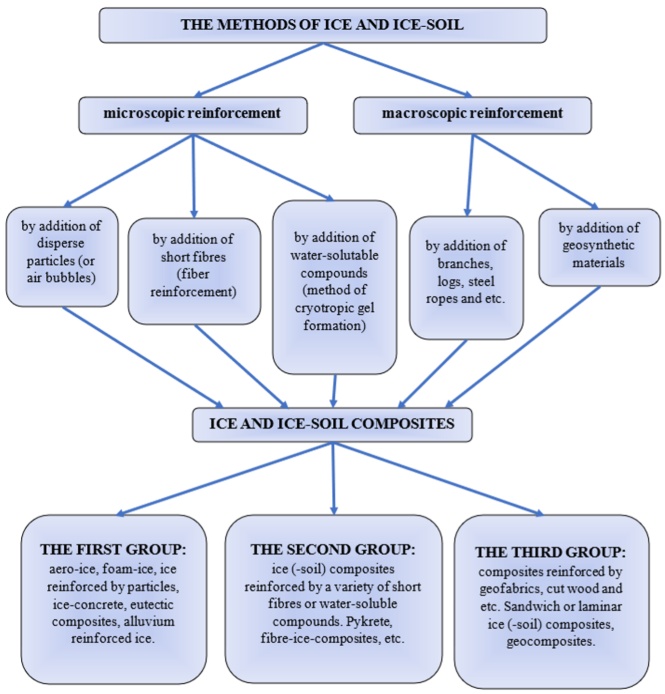


Figure 10: The methods of ice and ice-soil reinforcement [6].

Macroscopic reinforcement indicates that the size of the reinforcement particles is larger than that of the ice grains, such as rebar and trunk. Microscopic reinforcement means that the reinforcement particles size is comparable to the ice grains, such as sawdust, blast furnace slag, straw, etc. [6]. The most investigated reinforcement materials with the matching type of reinforcement are shown in Table 5. Among organic materials, sawdust and wood pulp were the most explored while glass fibre and geogrid were utilized the most among inorganic materials [6].

Several impacts that influence the performance of reinforcement can be listed: fibre-matrix stiffness, strain compatibility between the fibre and the matrix and fibre-matrix interfacial bond. It is of crucial importance to secure appropriate bonding between the matrix and reinforcement to transfer the load from one to another. It is recommended to use hydrophilic fibres rather than hydrophobic ones [6].

Table 5: Reinforcement materials and type of reinforcement [6].

Reinforcement material	Reinforcing type*	Frequency of use (1957–2015)
Glass fibre	Mi/Ma	7
Geogrid	Ma	2
Cryotropic gel	Mi	1
Steel	Ma	1
Slag	Mi	1
Asbestos fibre	Mi	1
Wood pulp (pykrete)	Mi	5
Peat mass	Mi	1
Hay	Mi/Ma	1
Straw	Mi/Ma	1
Sawdust	Mi	12
Newspaper	Mi	1
Paper dust	Mi	1
Twigs	Ma	1
Wood chips	Mi	3
Newspaper (mash)	Mi/Ma	1
Algae	Mi	1
Cotton (fibre/cloth)	Mi/Ma	2
Sand (silica, coarse)	Mi	2
Gravel	Mi	1

*Mi – micro, Ma – macro.

Igloo, Fig. 11, was the first and most famous building made of ice reinforced with lichen in polar regions of north hemisphere [6]. It was made in a traditional way by cutting bricklike elements out of snow or ice and stacking them together. Igloos are catenoid-shaped to avoid tensile stresses [9]. Thickness of igloo ice walls and details of the reinforcement could not be obtained from research publications.

During World War II, the reinforcement of ice has started to be investigated for military purposes. In Russia (former Soviet Union), ice bridges and ice roads were being strengthened with logs, branches, and twigs to enable heavy military transportation [6], while in the USA project Habakkuk took place [7]. It was a top-secret project with a goal to make an aircraft carrier out of seawater ice combined with 14% wood pulp. The material was named pykrete after its inventor Geoffrey Pyke [7]. Artificial cooling was

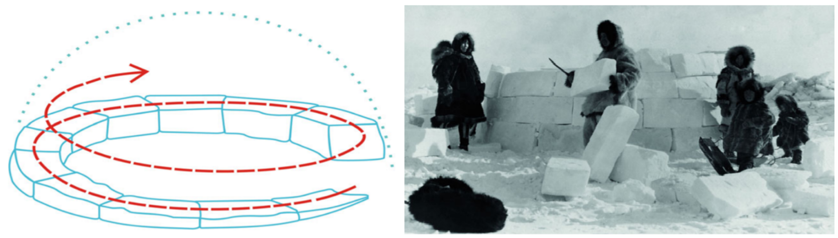


Figure 11: Construction of an igloo [9].

planned to shorten the freezing time of pykrete in the vessels. Although the project had huge support at the time, it is reported that several problems appeared and caused the work on the project to cease. First, engineers had insufficient knowledge about the physical properties of ice and therefore, were not positive whether it can perform its function safely. Also, they did not know how to build structures that can stand up to forces imposed by ice. In addition to that, as large quantities of pykrete needed to be frozen, requirements for an immense refrigeration capacity emerged. According to Gold [7], in many ways engineers have not gone forward in the understanding of ice since Habakkuk project.

In January 1961, the project Ice Way was conducted on floating sea ice on the North Star Bay, Greenland. To build an airstrip that can withstand heavy loads, three layers of parking pads were built on top of the natural ice [8]. The first pad was flooded with the sea water in 3 m thick layers, the second one had a thickness of 2 m and was reinforced with fibreglass mats at the top and the bottom and top pad was 1.5 m thick and made of ice chips, fibreglass reinforcement and saturated with sea water. Size and structure of reinforcing mats were not discussed. Successful aircraft landing, parking and take-off tests were conducted on the 4270 m long reinforced runway.

In the Glockner's paper, it was stated that reinforced ice domes represent an economical and practical solution to the problem of making temporary and semi-permanent enclosures that northern communities could use for various purposes, e.g., recreational centres, storage areas and workshops [3]. Dome structures make the best use of ice because of their much higher compressive than tensile strength. At the University of Calgary in Canada, 4 domes were created by spraying water with a compressed air-garden hose on the reusable inflatable membrane formwork. The first dome was a pilot, and the rest were made with, without or with some reinforcement. Dome number 2, Fig. 12, was fully reinforced with a network of glass fibre yarn, a reinforcement material chosen over nylon string and wire. The exact size and shape of the reinforcing network were not provided.

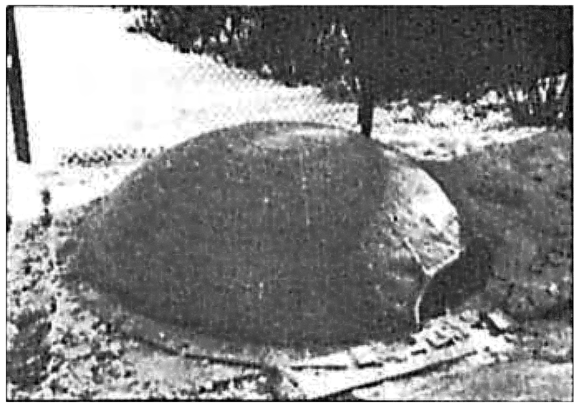


Figure 12: Dome made of ice reinforced with fibreglass [3].

Difficulties encountered during the construction process were freezing of the water in the nozzle, establishing the rate and fineness of application to form a layer of ice, and sun shining onto the fabric. It was necessary to ensure continuous spraying by circling the dome at an even rate as well as allowing water enough time to freeze before applying the next layer. After completing the construction, the inflatable was pulled loose from the internal surface of the dome. To test their load-carrying capacity, domes were loaded with sandbags. The tests have shown that reinforced ice domes have larger load carrying capacity and can withstand heavy loading even during higher temperatures, Table 6. It was concluded that reinforced ice can be a useful structural material and the spraying technique was proven successful on small-scale models.

However, questions arose about the requirements for appropriate spraying equipment and the rate of application of spray as well as the placing of the reinforcement network to a large-scale model. Glockner advised using insulation if exposure to the sun is unavoidable and insulating the interior of the structure to increase its lifespan. It was suggested that additional research work needs to be done in the thermodynamic aspect of reinforced ice structures, such as heat loss, ice conductivity and the effect of air boundary layers. In addition to that, further investigation of the creep deformation and behaviour was suggested.

Research work related to ice reinforcement has stagnated for a few decades until the early two-thousands when cryogel based on ice and PVA

Table 6: Construction and testing information of the domes [3].

Dome No.	Reinforce-ment	Hours of spraying, approx.	Volume of water approx. (l)	Average erection air temp. (°C)	Load (kN)	Load duration (h)	Air temp. at failure (°C)	Average ice thickness (mm)
1	None	–	–	–	–	–	–	–
2	Full network	3	54	–21.9	1.4	72	–	–
		1	23	–19.7	2.4	190	–5.0	12
		Total:	77					
3	None	1	18	–14.2	1.7	0.2	–12.0	15
		3	59	–14.1	–	–	–	–
		Total:	77					
4	Door region only	0.5	9	–13.2	2.4	29	+6.0	8
		2	40	–16.2	–	–	–	–
		Total:	49					

was used to seal a leakage at the base of a dame at the Russian Irelyakh hydro system [16]. Cryogels are polymer gels generated due to freezing and thawing cycles of an aqueous polymer solutions. Cryogels based on a PVA, with a cross-linking agent and electrolytes as additives, are widely used and have exceptional mechanical, thermophysical and diffusional properties. It has been emphasized that PVA cryogels are easily available, simple to produce, non-toxic and biocompatible. In 2003, 51 tons of cryogel-forming solution were injected into 5 holes at the base of a dam which formed a 3 m thick barrier that covered an area of approx. 430 m^2. The material was found reliable, hence the technology continued to be used in the following years. In the paper mass fraction of PVA in cryogel solution was not provided. Polyvinyl alcohol powder and fibre in combination with saltwater ice was proposed and tested for cold-region constructions [29]. Results showed that PVA reinforcement improved the compressive strength of saltwater ice from 10.1 to 29.6 MPa [29]. The experiments in the field of ice road crossing rivers are of high interest for Alaska, Canada, northern Russia, and Scandinavian countries. The tests including geonets and their applications as a reinforcement of ice covers were undertaken by a group of researchers, led by Sirotyuk and Yakimenko. They tested freezing geonets from above, Fig. 13, but also from below the ice cover. As the results of the test conducted from 2014–2015 have shown, reinforcement by the geonets from above improves the bearing capacity of the ice cover up to 30%. Loading tests on the ice cover reinforced from below pointed out up to 70% higher bearing capacity [15]. Reinforcement both from above and from below gave an excellent stabilizing effect. It has also been stated that the geonets and the geogrids can be easily removed and stored for future using what makes them environmentally acceptable solutions.

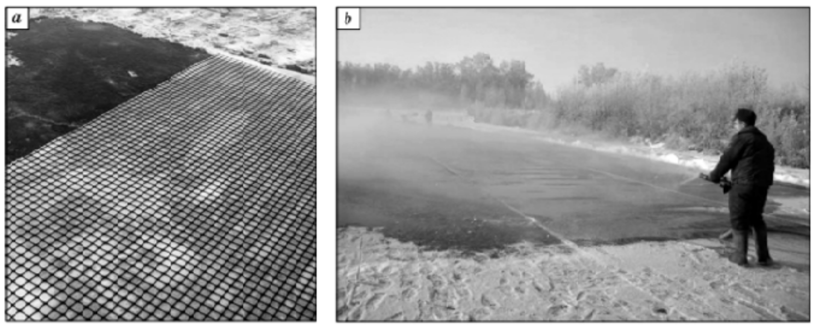


Figure 13: Reinforcement of an ice crossing from above [15].

In the winter of 2013, 30 m span Pykrete dome, Fig. 14, was built in Juuka, Finland by scientists and students from Eindhoven University of Technology [9]. The construction method was based on the research on ice shells conducted by Kokawa [27]. In the process of dome construction, instead of ice, a team led by Pronk used pykrete – a mixture of water and 10% fine sawdust. Information about the particle size of sawdust was not given. An inflatable polyethylene mould along with rope covers was fixed to the anchor points and inflated, after which a slush made from water and snow was applied to the foundation. It is not clear what spraying equipment was

Figure 14: Making of a pykrete dome [9].

used, what was the application rate and was there just one or more layers. The 150–400 mm thick dome was tested with sandbags that weighed 1850 kg and there was no deformation to measure. Afterward, pykrete samples were cut out and compared to pure ice. It was concluded that the spraying method creates ice of high quality and that the pykrete samples were stronger than the ice samples by 21%. However, pykrete samples were found nonhomogeneous with fibre reinforced ice making up only an average of 42% of the content. It was concluded that the usage of pykrete allows for even thinner shell thickness – which would lower the structure's dead load – and that the construction of an ice shell with a 100 m span is realizable.

The research continued in 2015 with the construction of the reinforced ice replica of Gaudi's Sagrada Familia [10], Fig. 15, and an attempt to make a replica of da Vinci's bridge, Fig. 16 [30], also in Juuka, Finland.

Figure 15: Construction of the Sagrada Familia in reinforced ice [10].

Figure 16: Render of the da Vinci's bridge in ice [30].

Creating of Sagrada Familia was an international project as, apart from the Eindhoven University of Technology, teams of students from Ghent University in Belgium also participated. The structure was built in the same manner as the pykrete dome, Fig. 17.

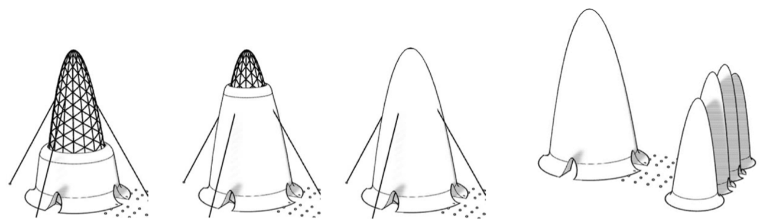


Figure 17: Schematic representation of applying pykrete around the inflated formworks [10].

Authors have stated that during the process several problems have occurred. To begin with, ice reinforced with sawdust was not homogeneous due to gravity and snow that kept falling during the construction time, so large safety factors needed to be adopted. Several delays were encountered as the outside temperature was around −5°C which is much higher than the ideal −20°C for instant freezing of pykrete. Strong wind has caused displacements of the structure and damaged the main tower which in the end was not finished completely. Finally, installations froze and there was a lack of electricity. It remained unclear how thick was the structure, as well as how much sawdust was added and what was the particle size.

Project Da Vinci's Bridge in Ice was inspired by Leonardo da Vinci's sketches of the bridge that was supposed to be built on the Bosporus River. A mixture of water and 2% cellulose was used and sprayed on the PVC inflatable in the same building process already used in the construction of the Pykrete dome and Sagrada Familia. However, due to unexpected changes in the weather conditions, i.e., above 0°C temperatures and rain, structural capacity was jeopardized what caused an implosion of the inflatable mould and the bridge was never built [30].

Candela pavilion, Fig. 18, was another similar project inspired by Felix Candela's famous reinforced concrete hypar shells and built by staff and students from the Ghent University a part of 'Juuka in ice' manifestation [30]. A mixture of 2% cellulose and water was used to make a 0.05 m thick pavilion with a span of about 15 m. Cellulose was chosen over sawdust as it is white which is more aesthetically pleasing. Also, it is easier to make a homogenous suspension when mixed with water [11].

Figure 18: The Candela pavilion [11].

Size of the cellulose particles was not provided. It is stated that mass percentage was not determined by the strength criteria, but the mixture needed to be fluid for it to be sprayed far enough. Besides from pavilion's complex geometry, a major challenge was a very low thickness to span ratio and unfavourable weather conditions, i.e., unusually high temperatures, wind, and snow. It has been concluded that the project yielded valuable data for future reinforced ice structures.

In winter 2017–2018 two ice shell structures were created: Flamenco Ice Tower, Fig. 19, and THRICE, Fig. 20, [12]. Both were made as a part of the Harbin Ice Festival.

Figure 19: The Flamenco Ice Tower [9].

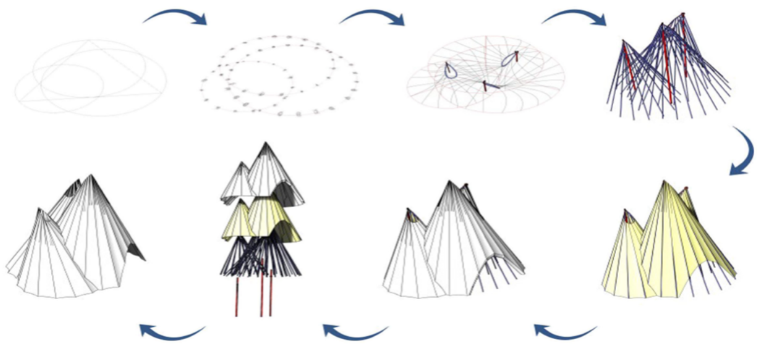


Figure 20: Assembly procedure of THRICE [12].

Flamenco Ice Tower was a joint project of students and professors from the Eindhoven University of Technology, Summa College, Harbin Institute of Technology, School of Architecture and School of Civil Engineering. It was inspired by the flamenco dress, the traditional Chinese tower, and the Harbin flower. A 30.5 m high tower with 6 surrounding shells holds the world record for the largest thin shell ice structure. The structure was made in pykrete – a mixture of 2% paper fibre (cellulose) with unknown particle size. The spraying technique was used in the same way as with the previously mentioned structures. Prior to the construction, calculations of the inflatable and of the shell structure were made, as well as finite element model in Ansys environment engineering software.

An ice pavilion THRICE, Fig. 21a, was inspired by the work of architect Heinz Isler and built by a team from the College of Architecture and Environmental Design, Kent State University in Harbin. THRICE consisted of three intersecting asymmetrical cones with an average thickness of 0.06 m and heights of 10 m, 8.5 m, and 7 m that covered an area of approx. 100 m^2. Aided by a computer model in Rhino, the structure was realized by spraying a mixture of water and cellulose on the membrane mould fixated with ropes, Fig. 20. Mass percentage and size of cellulose particles were not reported. It was observed that the deformations were larger than predicted which indicated a need to fully understand the connection between materials and forms used for creating the structure (ropes, oculi, and formwork) and the structure's material, thickness, and geometry.

It was emphasised that ice composite structures are still in the experimental phase with a lot of new possibilities that are yet to be discovered. However, several limitations were recognized such as the albedo effect, sub-

(a) (b)

Figure 21: (a) THRICE – an ice pavilion [12]. (b) The world's first sprayed net hyperboloid ice structure [31].

limation, creep behaviour and strong temperature dependency of the structure. In conclusion, it was stated that there is a need for a building code of ice composites as there is still no technical standard for ice shells nor for reinforced ice. The world's first sprayed net hyperboloid ice structure, Fig. 21b, was built during winter of 2018 by a group of student architects and engineers of the Design Research Centre, School of Architecture and Harbin Institute of Technology. A water mixture, with 0.6% cellulose and no particle size recorded, was used to form the reinforced structure. The novelty that was introduced was the spraying of rope nets and using the rope formwork. Because of the reinforced ice properties, a formwork that enables the transformation from the completely tensile structure in construction to the completely compressive structure when released was used [31]. Previously mentioned ice structures required sophisticated formwork while hyperboloid ice structure construction was low-cost, swift, and sustainable. The observed deficiency was the waste of the cellulose-water mix while spraying [31].

The ice composite shell structure, named Koi-fish after famous ornamental fish species, realized with complexly shaped inflatable formwork was made in Harbin Ice – Snow World festival in China. The Koi-fish shell structure, Fig. 22, was built with ice reinforced with 2% white pulp-fibre material [32]. Because of the material imperfections detected, reinforced ice specimens at heights of two and four metres were collected. Density test, fibre mixing ratio test, as well as compressive and tensile strength tests, have been carried out. It has been concluded that the ice composite density performs a normal distribution. Also, the material delamination effect on the bearing capacity, which occurs because of an unequal composite mixing while spraying, was investigated. It was shown that the material delamination has a serious material strength lowering effect [32]. Also, it was concluded the monitoring thickness was higher than the designed one and the temperature and material thickness directly affect the bearing capacity of the Koi-fish ice shell. The main surface scanning was used to compare and examine the drawbacks between the actual surface and the model. It is emphasized the spraying technique must be improved to create a satisfying quality of the reinforcement.

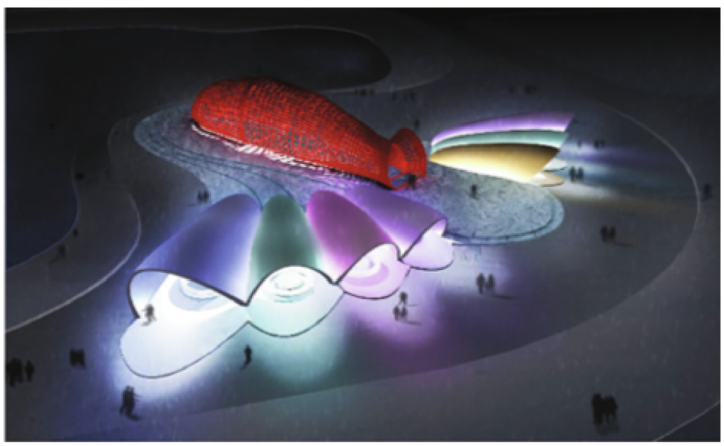


Figure 22: The Koi-fish ice shell [32].

The construction process and the design details of the ice shell restaurant, Fig. 23, were elaborated in [14]. Ice restaurant occupied 554 m^2 and could receive up to 40 people at once. Two types of inflatable mould, the airbag mould, and the air rib mould, were compared and the superiority and peculiarity of the air ribbed inflatable mould construction process, used for this structure, was discussed. The reinforcement material was 2% paper fibre because of its improved material properties compared to pure ice. Particle size was not mentioned. The structural behaviour under 10 different load conditions was analysed. As the fundamental variable for a finite analysis for the average test strength reinforced ice at $-15°C$ was used. It was concluded that the results of the maximum tensile and the maximum compressive stress of the structure were under safety requirements. Buckling tests were not discussed.

Figure 23: Ice restaurant at the 21st Harbin Ice and Snow World [14].

Summary of reviewed papers dealing with ice structures was given in Table 7 where used reinforcement materials are synthetised, while in Table 8 construction methods and parameters are presented. It can be noted that for most ice structures construction parameters were not completely defined and nor was the size of reinforcement material.

All presented structures have been made from frozen plain or seawater, both of which are easily available in cold areas. However, if tap water is used, the cost of it should be considered as well as the cost of artificial cooling if needed. Various types of used reinforcement materials proved to be economical and environmentally friendly. Lichen has no economic value so building an igloo is cost-free. Furthermore, as lichen is a sustainable natural material, there is no waste when using it. Logs, branches, and twigs are also sustainable biodegradable materials, and their usage can be considered economical. Similar non-toxic, low-cost biodegradable materials are cellulose and pulp fibres which have been widely used in recent years. Sawdust is already a waste and therefore a low-cost material. However, it is not always available in large quantities. On the contrary, fibreglass, and PVA are much pricier than mentioned natural materials. PVA is a non-toxic and biodegradable material while fibreglass can be toxic and is not biodegradable. Given the economic and environmental aspect, most of the structures were found to be economical and environmentally acceptable.

Table 7: Reinforcement materials used for ice structures.

Reference	Time	Structure	Reinforcement			Aspect	
			material	mass fraction	particle or net size	environmental	economic
[6,9]	ancient times	igloo	lichen	n/a	n/a	no	no cost
[6]	1941–1942	ice bridge	logs, branches, twigs	n/a	n/a	no	economical
[7]	1942–1943	aircraft carrier	wood pulp- sawdust	14%	n/a	no	economical
[6,9]	1943	ice road	logs, branches, twigs	n/a	n/a	no	economical
[8]	1961	ice airstrip	fibreglass	n/a	n/a	yes	moderate cost
[3]	1976	ice dome	fibreglass yarn	n/a	0.87 mm	yes	moderate cost
[16]	2003–2005	watertight elements in dams	polyvinyl alcohol	n/a	-	no	expensive
[15]	2011–2015	ice roads crossing rivers	geonets from fibreglass	n.a.	4 m × 50 m, 4 m – 30 m, 2.4 m × 50 m	yes	moderate cost
[9]	2013–2014	Pykrete dome	fine sawdust	10%	n/a	no	economical
[10]	2015	Sagrada Familia in ice	fine sawdust	n/a	n/a	no	economical
[11,27]	2015	Candela pavilion	cellulose	2%	n/a	no	economical
[27]	2015	Da Vinci's bridge	cellulose	2%	n/a	no	economical
[12]	2017–2018	Flamenco Ice Tower	cellulose	2%	n/a	no	economical
[18]	2018	hyperboloid-net ice structure	cellulose	0.6%	n/a	no	economical
[28]	2017–2019	THRICE – ice pavilion	cellulose	n/a	n/a	no	economical
[29]	2019	Koi-fish ice shell	white pulp fibre	1%	n/a	no	economical
[14]	2019	Ice restaurant	paper fibre	2%	n/a	no	economical

Table 8: Construction parameters engaged in building ice structures.

Reference	Time	Structure	Place	Construction parameters		
				construction method	wall thickness	cooling method
[6, 9]	ancient times	igloo	northern regions of Canada, USA and Russia (Eskimos, Chukchi)	brick stacking	n/a	not used
[6]	1941–1942	ice bridge	Ice railway bridge over Dnieper, Ukraine	freezing in layers	n/a	not used
[7]	1942–1943	aircraft carrier	Project Habakkuk, Canada, Great Britain	freezing in layers	n/a	artificial cooling planned
[6, 9]	1943	ice road	Ladoga Lake Life Road USSR	freezing in layers	n/a	not used
[8]	1961	ice airstrip	Arctic region, USA	freezing in layers	approx. 5.5 m	not used
[3]	1976	ice dome	Calgary, Canada	spraying water on an inflatable with reinforcement at below 0°C	n/a	not used
[16]	2003–2005	watertight elements in dams	Irelyakh hydro system, Siberia, Russia	51 t of cryogel forming solution injected into dam holes and frozen	3 m	not used
[15]	2011–2015	ice roads crossing rivers	Arkhangelsk region, Russia	geosynthetic material froze into the ice	n/a	not used
[9]	2013–2014	Pykrete dome	Juuka, Finland	spraying suspension of water and reinforcement on an inflatable at below 0°C	0.04 m (base), 0.15 m (top)	not used
[10]	2015	Sagrada Familia in ice	Juuka, Finland	spraying suspension of water and reinforcement on an inflatable at below 0°C	n/a	not used

Table 8 [cont.]

Reference	Time	Structure	Place	Construction parameters		
				construction method	wall thickness	cooling method
[11, 27]	2015	Candela pavilion	Ghent, Belgium	spraying suspension of water and reinforcement on an inflatable at below 0°C	avg. 0.05 m	not used
[27]	2015	Da Vinci's bridge	Juuka, Finland	spraying suspension of water and reinforcement on an inflatable at below 0°C temperatures	n/a	not used
[12]	2017–2018	Flamenco Ice Tower	Harbin, China	spraying suspension of water and reinforcement on an inflatable at below 0°C	0.07 m at the top, 0.04 cm at the bottom, 1 m foundation	not used
[28]	2018	hyperboloid-net ice structure	Harbin, China	spraying mixture on the net formwork at below 0°C	n/a	not used
[19]	2017–2019	THRICE – ice pavilion	Harbin, China	spraying suspension of water and reinforcement on an inflatable at below 0°C	avg. 0.06 m	not used
[29]	2019	Koi-fish ice shell	Harbin, China	layer spraying cellulose-water mix on an inflatable formwork at below 0°C	0.05–0.15 m at the top, 0.05–0.25 m at the bottom	not used
[14]	2019	Ice restaurant	Harbin, China	spraying ice composite material on an air ribbed inflatable mold at below 0°C	0.2 m at the bottom, 0.1 m at the top	not used

4 Conclusions and future directions in field

This paper focuses on the examination of existing research studies related to reinforced ice and reinforced ice structures. Ice structures covered so far in research findings were presented with an emphasis on construction and reinforcement parameters. It was found that ice is very suitable for usage in various fields of engineering applications, but there is still insufficient knowledge of its behaviour when used as a building material. Its properties vary and are not entirely suitable for building purposes. However, thermophysical properties of ice can be significantly improved by reinforcement. Presented data shows that, with introduction of sawdust, thermal conductivity and diffusivity of pure ice can be decreased by 21% and 23%, respectively. Different kinds of reinforced ice may have up to 4–6 times higher compressive, tensile, and flexural strength than plain ice as well as lower creep rates and an improvement of brittle behaviour. For instance, ice reinforced with wood pulp (pykrete) was found to have up to 2 times higher tensile strength than concrete. Possibilities of reinforcement are numerous and there is a wide range of choices with respect to application, availability, and cost-effectiveness. Cellulose derivatives have demonstrated the best physical properties with being environmentally friendly and economically viable. However, in the analysed studies several issues were observed. In most of the studies construction parameters – construction method and wall thickness – were not defined accurately and nor was the size of reinforcement particles or nets. There is a necessity to define a procedure of preparation of ice composites for practical purposes. It is crucial to know the effects that reinforcement type, size, quantity (mass or volume fraction percentage), positioning, and distribution have on the final product. Furthermore, the freezing process and ways that ensure reinforcement material stays in the desired position during the process should be defined. Overall, it can be concluded that there is a necessity for more comprehensive, clear, and accurate data regarding reinforced ice construction methods and processes, as well as regarding the preparation of ice composites in general.

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