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Design and Realization of CSSRC Small Ice Model Basin for Ice-related Fundamental Researches

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ABSTRACT

A small ice model basin (SIMB) has been newly constructed in China Ship Scientific Research Center (CSSRC) and put into use for ice-related fundamental researches such as ice modeling, determination of ice mechanics and investigation on ice-structure interaction, etc. The basin has a dimension of 8m in length, 2m in width and 1m in depth. Numerical simulation was applied to optimize the temperature field and the arrangement of cooling air circulation passage. Columnar saline ice is made from thin sodium chloride solution with an accurately controlled process of pre-cooling, freezing and tempering, which incorporates with seeding at the beginning and micro bubbling in the operation of freezing. A series of measurements of physical and mechanical properties along with microstructure observations of the resulted model ice have verified the main design aspects well, and, the realization of SIMB can make an effective platform for some basic studies on ice.

KEY WORDS: Ice basin; Columnar saline ice; Cooling simulation; Ice making; Measurement.

INTRODUCTION

The demands for development of ice-going vessels and arctic offshore structures as well as their operations are booming in China under the background of Polar Silk Road international cooperation.

However, the knowledge and expertise are generally not so abundant for Chinese designers and engineers who are involved in this field and urgently desiring physical testing in model ice versus real ice covered waters.

More and more fundamental researches and engineering exploitation are undergone nowadays to make the situation better. While currently not so many experimental facilities are available for this purpose in China except for only one ice tank running in Tianjin University, which was built at its new campus in 2016.

On the other hand, there have been ever run quite a few ice model basins/tanks worldwide, and for the major existing ones, which are active and competitive, main information of the respective model ice is shown in Table 1. The main ice types in current ice basins are column ice and fine grain ice. The chemical composition and solution concentration are nearly different in each ice basin.

Table 1. The model ice information of the major active ice basins in the world

Dimension				Model ice			
BASIN	L (m)	W (m)	D (m)	Ice Type	Chemical composition	Concentration	Air Bubbling
Aalto	40	32	2.5	f	Ethanol	0.3 %	no
Aker Arctic	75	8	2.1	f	NaCl	1.4 %	no
HSVA	78	10	2.5	c	NaCl	0.7 %	micro
NMRI	35	6	1.8	c	Propyl.Glycol	0.3 %	yes
Krylov	102	10	2	f	NaCl	1-1.5%	no
Kriso	42	32	2.5	c	EGAD	0.39%	micro
NRC	90	12	3	c	EGADS	0.39%	no

Evidently, to fulfill a large ice model basin, it is a good way to have a try as first step with a small one, with reference to the histories of the major basins and the success of the pioneers, such as Timofeev, O.Ya. (2015), Katsuyoshi Takekuma (1987), Kostilainen, V. (1987), Wilkiman, G. (2006) and Lee, C. J. (2007), etc.

The design of such a small ice model basin (SIMB) was carried out in China Ship Scientific Research Center (CSSRC) with expectation to gain its own experience about facility and technology for ice modelling and testing. Numerical simulation was made for the design to optimize the temperature field and cooling air circulation. The construction of the main body was completed by the end of 2016. After that, instruments and apparatus were gradually implemented and the methodology of ice making was tried out step by step and finally fixed. The realization of SIMB was verified by a series of scientific measurements on the resulted model ice, and, having effectively facilitated the development of ice-related technologies in CSSRC.

GENERAL LAYOUT AND PRINCIPAL PARTICULARS

The construction of CSSRC SIMB makes use of an existing two-story building with an overall area of 140m^2. Under this limitation, there should be arranged ice basin, cold room, control room, power room and office for operators, etc. The machinery room has to be additionally built outside the building, to contain the refrigerator units and accessories. The general layout is as shown in Figure 1.

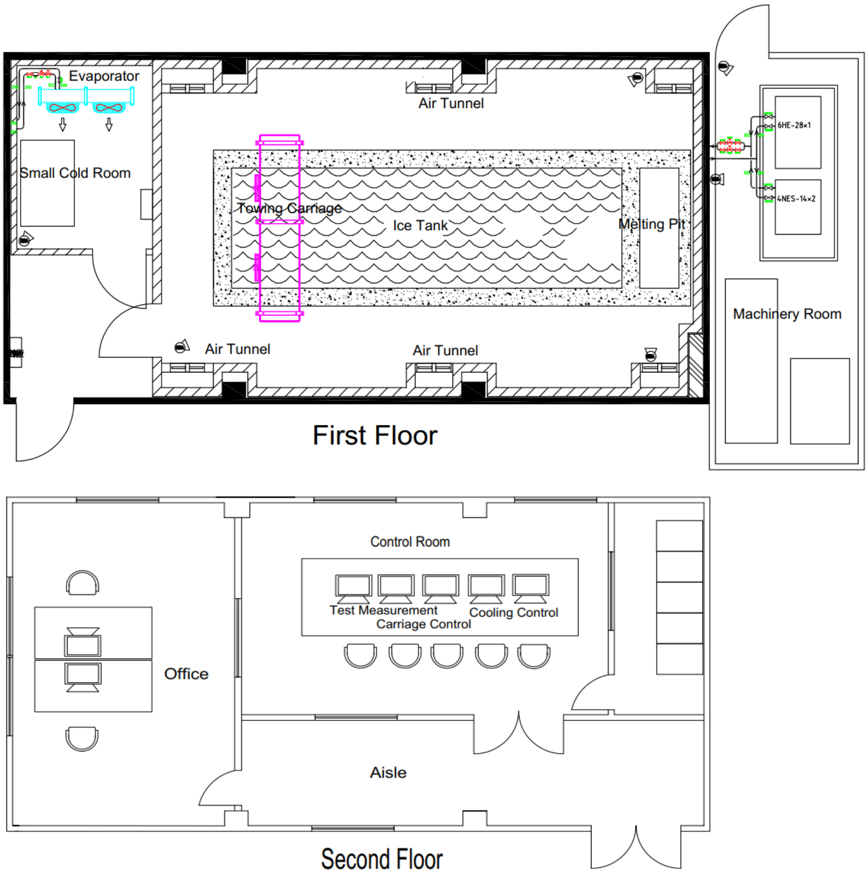

Figure 1. Plan and arrangement of CSSRC SIMB

The room housing the ice basin is quite small, only with a total net volume of about $300m^3$ (10m(L)×6m(W)×5m(H)). To the upper limit which can be reached the dimension of the basin is set as 8m in length, 2m in width and 1m in depth (see Figure 2).

Figure2. Interior scene of CSSRC SIMB

The entire room of the basin is fitted by thick polystyrene foam plate with stainless steel surface to make a well-insulated space to withstand the designed lowest temperature of -30℃ inside. Cooling fans are suspended from the roof and ceiling panels with tiny holes are installed underneath to exhaust cooling air and circulating fans with guide plates are set on the side walls to suck the air used for cooling, thus, forced cooling air circulation is formed. Numerical simulation counting porous boundary was established to model the air-flow distribution of the basin with air supply from perforated ceiling. Enthalpy-porosity model was applied to simulate 3D icing with air forced convection, and, based on un-uniformity analysis, the air-flow distribution hence the temperature field was optimized, as shown in Figure 3 with legend for temperature in Kelvin degree (273.15K≈0℃), to find the idea arrangement of cooling air circulation passage and adjust the main ducts above the ceiling and on the side walls.

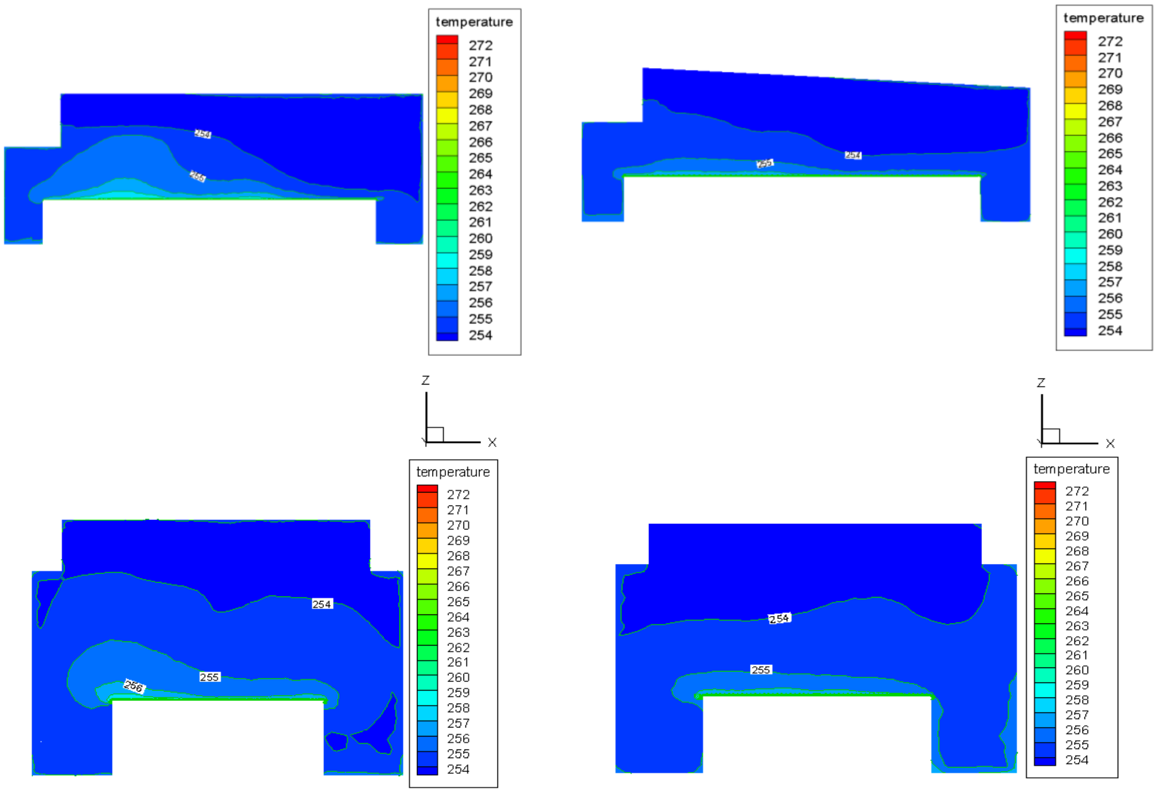

Figure 3. Temperature field optimization for icing

The basin is constructed with heavily reinforced concrete. Waterproofing agent and coating on inner surfaces are adopted to prevent water leakage. On top of the both side walls of the basin the rails for towing carriage are deployed with chairs.

There is a melting pit connected to the basin at the west end. It is fabricated with stainless steel with a net volume of 2m3 and electric heater inside.

The cold room with a size of 3m(L)×2.2m(W)×2.8m(H) is close adjacent to the basin for ice mechanics tests. The air temperature inside the cold room can be controlled in the range of -15℃~5℃.

MAIN EQUIPMENT AND INSTRUMENTATION

The SIMB is mainly equipped with cooling system, air bubbling system, towing carriage, and ice mechanics measurement devices, etc.

The cooling system as illustrated in Figure 4 consists of three sets of piston compressors using Freon as cooling liquid. One of the compressors has a power of 28hp. The other two smaller compressors have together a total power of 28hp. The operation of three compressors within different power levels makes the cooling system operation more flexible and efficient. The air temperature can be controlled by cooling fans hanging down from the ceiling. During ice freezing, cold air is blown down from the ceiling and sucked by the circulating fans located on different positions of the side walls. For the cold room, a separate refrigerator of 14hp is employed.

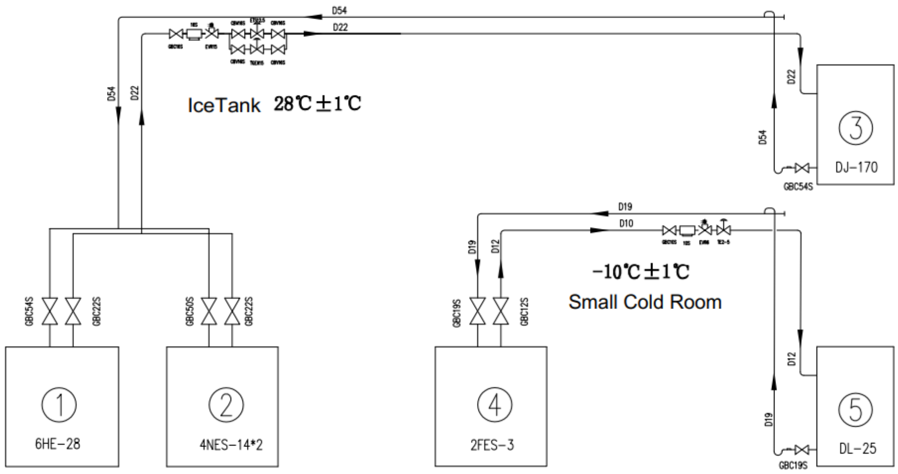

Figure 4. Flow sheet of cooling system

The air bubbling system to control the ice density and to adjust the ices strength supplies a mixture of water and air via a grid of pipes laying at the bottom of the basin to the water body. It consists of a water tank, a pump, a filter, the pipe grid and several valves as well as flow meters and oxygen sensors. The valves are magnetically operated to allow a control of amount of air being transported to the basin. The pipe grid consists of 16 pipes of 2m length with 20 holes having a diameter of 0.2mm and a distance of 100mm between each other.

The towing carriage shown in Figure2 is 2.4m wide and 1.2m long running on 2 rails mounted on both side walls on the basin. Its weight is 1.5 tons while the maximum towing and/or pushing capability is 3kN. It has a rack rail driving system powered by an electric AC engine of 5 kW. The speed range of the towing carriage is 0.01 to 1 m/s with precise control manually in situ or remote automatically in the control room. At the front the carriage is outfitted with a pushing plate for ice removal while at the rear a linear axis is installed to mount equipment for ice property testing.

The SIMB has been instrumented for the determination of physical and mechanical characteristics of model ice. The measured properties include ice sheet thickness, density, temperature, salinity, as well as uniaxial compressive strength, flexural strength and elastic/strain modulus, etc. The microstructure investigation of model ice can be performed with a four-axis universal stage and HD cameras. Data acquisition systems have also been configured for fundamental researches, while some other devices are under developing.

TECHNIQUES FOR ICE MAKING

The model ice fabrication methodology is adopted in this SIMB as that developed by HSVA Evers (1993). Columnar saline ice is made from thin sodium chloride solution with accurately controlled operation of pre-cooling, freezing and tempering, which incorporates with seeding at the beginning and micro bubbling in the process of freezing. Up to now many efforts have been made to repeatedly adjust the controlling parameters including freezing temperature and bubbling scheme and the techniques for ice making have been preliminarily established.

The pre-cooling is as a routine started to set the initial conditions for making a new ice sheet. Then the seeding procedure starts using the spraying gun installed on the towing carriage. The carriage is moved slowly during seeding and the small ice crystals settle on the cooled water surface with uniformity to nucleate the ice.

The cooling/freezing process is started after seeding, the ice sheet begins to grow by switching on the cooling system until approaches the target thickness. The cooling temperature of -16℃ or so is kept for the growth of model ice, and the growth speed is approximately 1.8mm/h. The underwater air bubbling system is switched on and operated accurately throughout the process.

The "Warm-Up" to temper the ice works with the "Turn Off" of the cooling system and "Turn On" of the heating system. Depending on the target of ice strength properties, the working power and time length of the heating system is correspondingly adjusted.

A typical time history of the temperature variation inside the basin is as demonstrated in Figure 5.

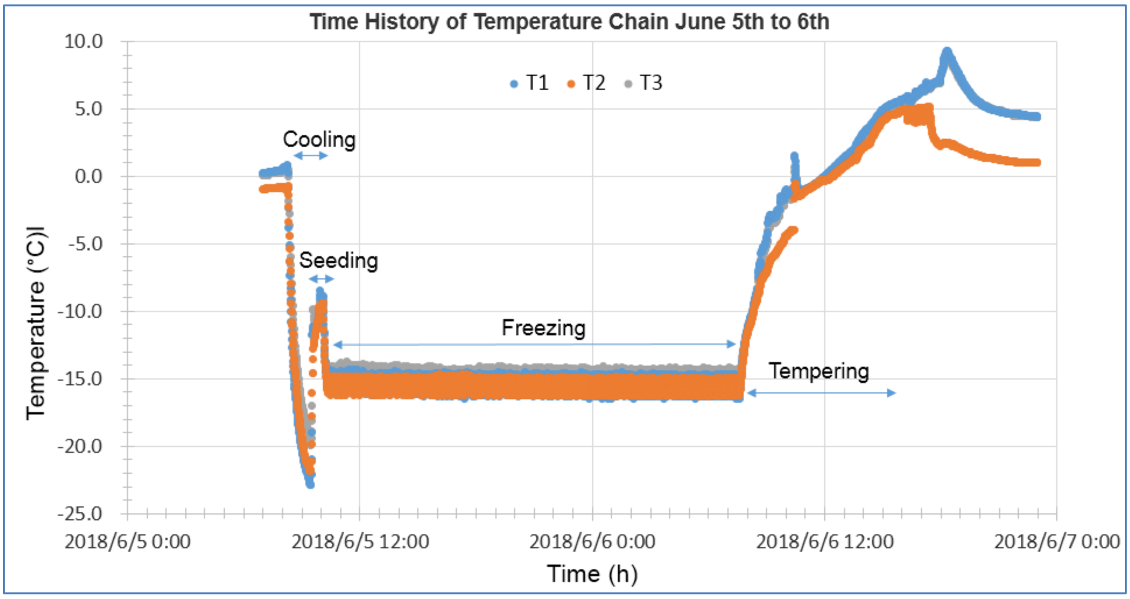

Figure 5. Time history of controlled air temperature

TESTING ON MODEL ICE

The distribution of the model ice thickness, cantilever beam flexural strength/elastic modulus are measured in-situ, as shown in Figure 6, for the purpose of uniformity and icing quality validation. The measurement locations are selected along width and length directions of ice sheet. A typical time history of the load during cantilever beam bending tests is as illustrated in Figure 7. The flexural strength is derived by

$$\sigma_f = \frac{6PL}{Bh^2} \tag{1}$$

Where P is peak force, L is beam length, B is breath of bean, h is ice thickness.

The elastic modulus can be obtained from

$$E = \frac{3}{16}\frac{1-\nu^2}{\rho_w g h^3}\left(\frac{F}{\delta}\right)^2 \tag{2}$$

Where ρ_w is water density, g is gravity acceleration, ν is Poisson's ratio, h is ice thickness, δ is plate deflection.

Values for thickness and flexural strength distributions are taken separately and the results are shown in Figure 8 and Figure 9. There are some discrepancy observed in the distribution towards the sides of the ice basin, but no more than 5% on the entire ice sheet.

Figure 6. Flexural strength / elastic modulus measurements on ice sheet

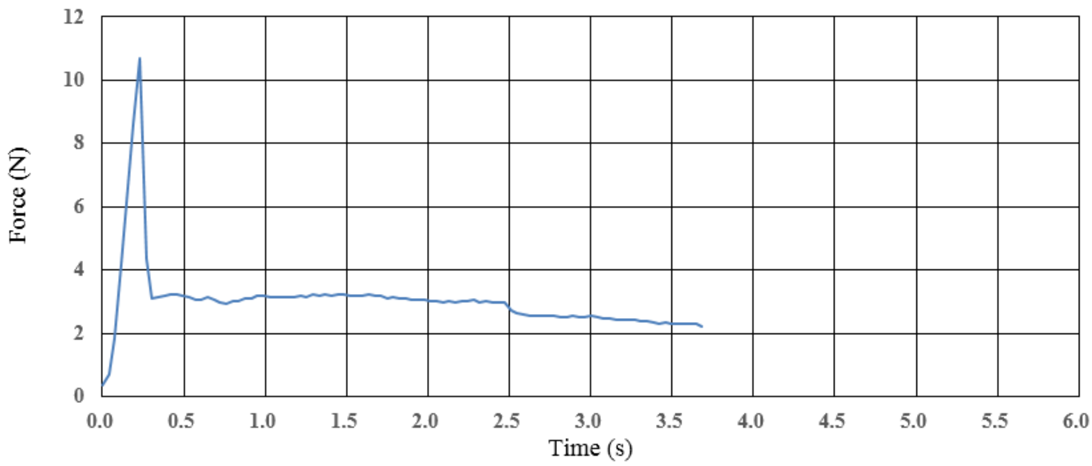

Figure 7. Time history of the load during cantilever beam bending tests

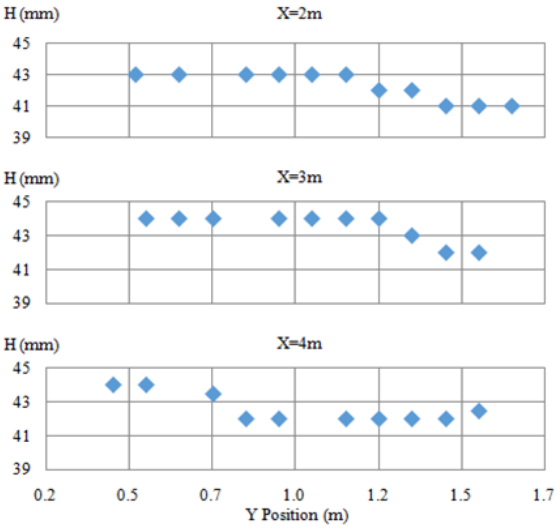

Figure 8. Distribution of ice thickness at different positions of ice sheet

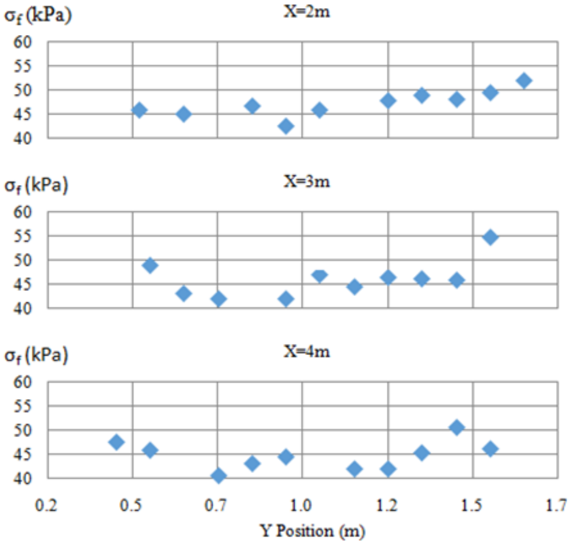

Figure 9. Distribution of flexural strength at different positions of ice sheet

The uniaxial compressive strength testing and crushing strength testing are also conducted following ITTC (2017) guidelines to qualify the model ice and further verify the SIMB design. The former is performed on model ice specimen with a material testing machine (MTM) in the cold room ex-situ the basin, while the latter is accomplished on the ice sheet in-situ with an intender moved by the towing carriage, as illustrated in Figure 10. The strain rate can be calculated using the equation as

$$\dot{\varepsilon} = \frac{\varepsilon}{t} = \frac{\Delta l}{tL} = \frac{v}{L} \tag{3}$$

Where $\dot{\varepsilon}$ is strain rate, ε is strain, t is fracture time, Δl is displacement, L is specimen length, v is crosshead speed.

The compressive strength is determined by

$$\sigma_c = \frac{P_f}{Bh} \tag{4}$$

Where, P_f is peak load, B is ice breadth, h is ice thickness.

Typical results revealing the fracture time and stress of the model ice varying with strain rates are given in Figure 11.

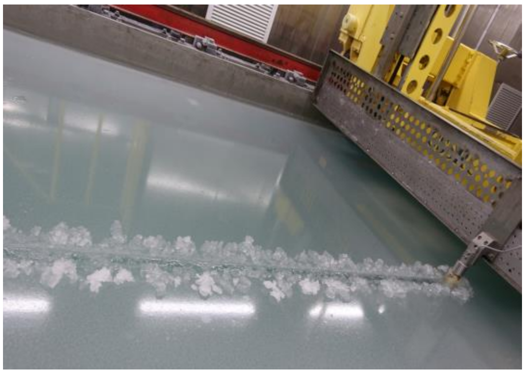

Figure 10. Uniaxial compressive strength testing and crushing strength testing

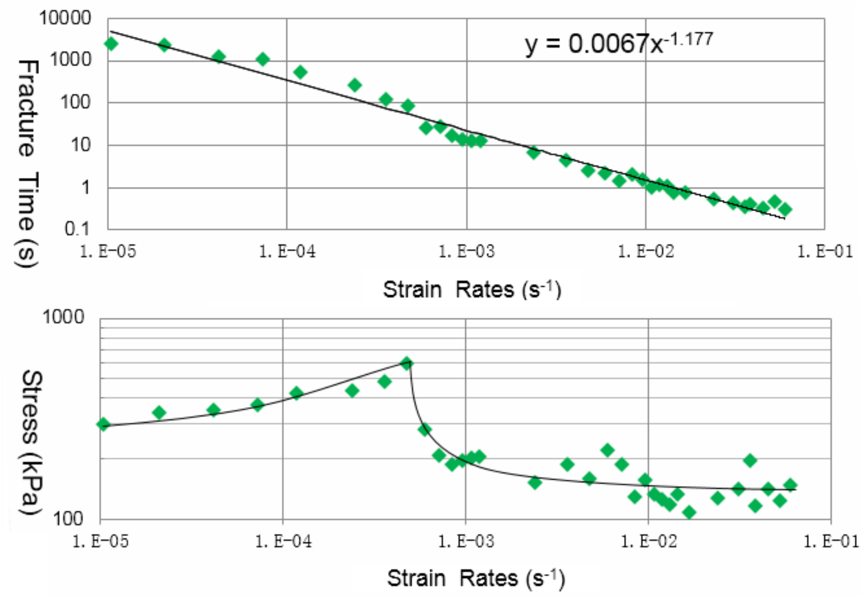

Figure 11. Curves of fracture time and stress varying with strain rates

To statistically analyze the major properties of the SIMB through a series of measurements, the density is about 0.90~0.91 Mg.m^{-3} at its initial flexural strength of 80~150kPa, compressive strength of 250~450kPa and elastic modulus of 80~200MPa. The ratio between elastic modulus and flexural strength of the model ice at initial phase, as well as the ratio between its flexural strength and compression strength, are 800~1500 and 2.5~3.0, respectively. The main characteristic parameters of the model ice in SIMB, CSSRC, are as summarized in the following Table 2.

Table 2. The main characteristic parameters of the model ice in SIMB, CSSRC

Properties	Values
Density($Mg.m^{-3}$)	0.90~0.91
Thickness (mm)	10~100
Flexural Strength (kPa)	80~150
Compressive Strength (kPa)	250~450
Elastic Modulus (MPa)	80~200
Elastic Modulus/Flexural Strength	800~1500
Compressive Strength/Flexural Strength	2.5~3.0

An example of the microstructure of the model ice is also as given in the following Figure 12. The documented ice fabric evidences that the model ice is composed of two distinct layers, i.e., the thinner top layer and the thicker bottom layer with average air bubbles of 200~500um in diameter trapped among the crystal structures. In general, the pattern of the resulted columnar model ice is close to those from other advanced basins though there is still big room for improvement.

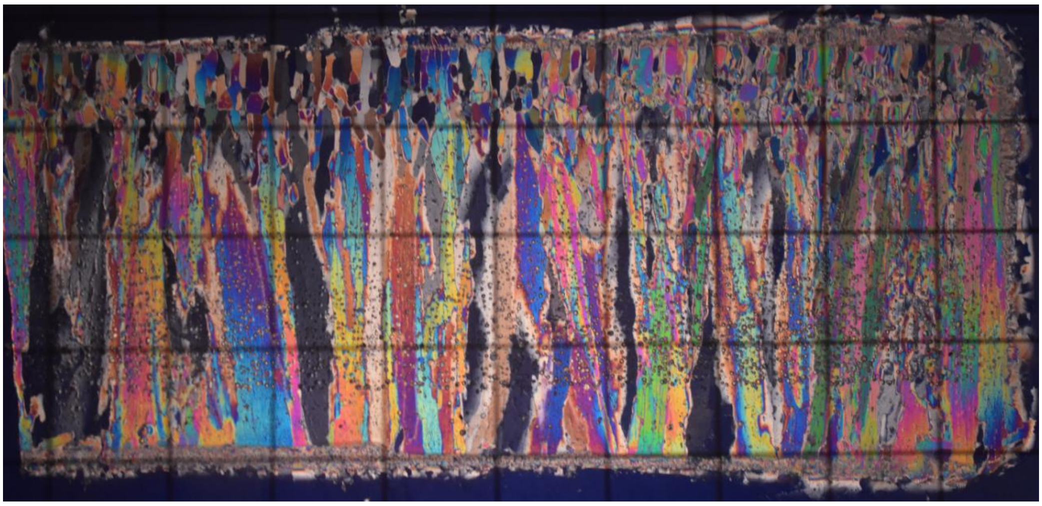

Figure 12. Columnar structure of saline model ice in SIMB, CSSRC

CONCLUSIONS

China Ship Scientific Research Center (CSSRC) has obtained the first experience in ice modelling and testing throughout the construction and application of its small ice model basin (SIMB), which would provide an effective platform for ice-related fundamental researches.

The all-round practice in ice making and examination on the resulted model ice have well verified the main design aspects of the SIMB, and, helpfully facilitated CSSRC the development of relevant technology and promotion of expertise on ice.

Furthermore, the realization of SIMB has enhanced CSSRC with a meaningful practice to extend its facilities somehow to meet the research and development aspirations of Chinese ice community and ship building industries.

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