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# Experimental Tests on the Consolidation of Broken and Brash Ice

Robert BRIDGES[1], Kaj RISKA[1,2], Andrea HAASE[3]

[1] Total SA, La Défense, France
[2] Presently at Delft University of Technology, Netherlands
[3] HSVA, Hamburg, Germany

## ABSTRACT

Accumulations of broken ice can pose challenges for ice engineering applications, such as rubble accumulations around offshore structures and brash ice in ports. It is thus important to understand the properties to enable reliable assessments of the impact they might have on facilities or to ship navigation. To improve the understanding of the different brash ice parameters, and especially those involved in the consolidation process, a series of experimental tests have been conducted. The tests included variations in parameters including the porosity, salinity and thickness of the brash ice. A series of measurements were made over the consolidation period. Namely those were salinity and compressive strength measurements of cores taken from consolidated brash ice and temperature profiles within the brash ice. The results provide insight into the processes in the brash ice during freezing. The paper presents an overview of the tests, measurements and results. The findings from these tests provide an improved understanding of the consolidation process which can be incorporated into modelling techniques for marine design and operations.

KEYWORDS: Broken Ice; Brash Ice; Rubble Ice; Consolidation; Compressive Strength; Salinity.

# 1. INTRODUCTION

The topic of broken, rubble and brash ice, i.e. ice pieces that are of small size (hereinafter generally referred to as brash ice), plays an important role in marine design and operations. This includes the determination of ice actions on ships, structures, berths and ice barriers. In particular brash ice can influence vessel icebreaking performance especially in manoeuvrability and ship behaviour. Brash ice is also created during ice management operations impacting the performance and safety. This is outlined by Riska et al. (1997) and Liferov et al. (2018), amongst others. Brash ice and rubble accumulations are also present in ports, channels and terminal areas which can impede operations if sufficient amounts are present, as described by Sandkvist (1986). It is also evident that rubble ice pieces interact during ice encroachment onto facilities and other fixed structures, and may also create obstacles or barriers in emergency situations, for example as noted by Allyn (1979), Mckenna et al. (2008), Croasdale (2012), and Barker and Timco (2016), to mention just a few. Some illustrative examples of these conditions are given in Figure 1-1. It is therefore clear that in order to take adequate action in managing broken, brash and rubble ice, the physical understanding of the mechanical and thermal properties of brash ice should be reliable, this results in adequate prediction methods for brash ice growth and action by brash ice. The aim of this work is to further develop and validate knowledge on processes involved in formation and thickness growth of brash ice.

*Figure 1-1. Examples of brash ice in ship channel (left image) and compacted brash ice during berthing (right image).*

The objective of this study is to investigate the question of brash ice thickness growth and in particular the influence of consolidation of brash ice in this process. For example, the freezing of the ship channel edges is considered of importance, as these are difficult for icebreakers to break and also in making the channel width narrower. Recent brash ice growth models, for example see Riska et al. (2019), include the cyclic ship breaking and refreezing process and are based on extension of earlier growth models which modify the Stefan type growth modelling. In this model the brash ice layer is divided into three layers (instead of two in earlier models) with the following:

- Brash ice above the water level, here the pores are filled with air (called 'dry brash ice')
- Solid ice frozen from brash ice below the water level
- Brash ice below the solid ice where the pores are water filled (called 'wet brash ice')

There is, however, a need for further understanding of brash ice growth processes in these layers. For example, the modelling of the brine rejection in freezing is not taken into account and improved comprehension is needed on the influence and modelling processes for variations in porosity and consolidation in a range of ice thicknesses. To investigate this, experiments have been performed to determine the brash ice consolidation properties so they may be utilised in developing design standards and methods for Arctic ports and ships projects.

## 2. EXPERIMENTAL SET UP

The brash ice testing programme was performed at HSVA Arctic Environmental Test Basin (AETB) with the aim of exploring the parameters influencing brash ice growth. In particular the objectives of the brash ice testing were to investigate the influence of salinity, brash ice porosity and brash ice thickness, and the resulting change of properties on the consolidation process.

### 2.1. Test Matrix

Two ice sheets using natural ice were used to make two series of tests. Each series was made with three ‘brash ice boxes’. In the first set of tests the brash ice thickness was varied in each of these boxes, and in the following series the salinity and porosity was varied in each of these boxes, as illustrated in Figure 2-1 and Table 2-1. Once the brash ice boxes had been prepared the room temperature was kept at around -15°C for 48 hours in the first series and for 168 hours in the second series. During the tests continuous and intermediate measurements were made (at 24, 48, 72, 144 and 168 hrs) to observe the consolidation process.

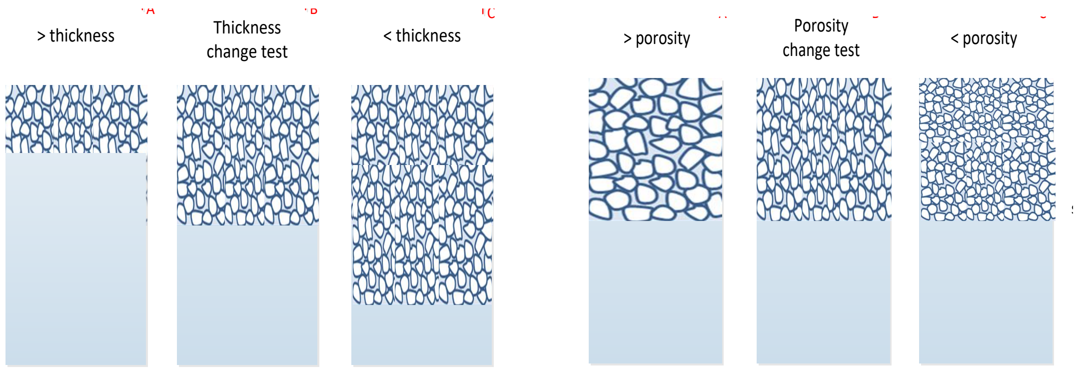


*Figure 2-1. Illustration of cross section view of boxes with variations in brash ice thickness (left images) and porosity (right images).*

*Table 2-1. Test matrix of target properties for brash ice boxes with variations in salinity variation (upper three rows vs. lower three rows), in brash ice thickness (upper three rows), and in porosity (lower three rows).*

| ID | Salinity, % | Parent level ice thickness, mm | Brash ice thickness, mm | Porosity |
|---|---|---|---|---|
| 1100 | 0.5 | 27 | 150 | 0.2 |
| 1200 | 0.5 | 27 | 230 | 0.2 |
| 1300 | 0.5 | 27 | 310 | 0.2 |
| 2100 | 3.0 | 15 | 230 | 0.1 |
| 2200 | 3.0 | 27 | 230 | 0.2 |
| 2300 | 3.0 | 38 | 230 | 0.3 |

### 2.2.Measurements

In order to investigate the consolidation behaviour of the brash ice, continuous temperature measurements were performed inside the brash ice boxes. In addition to the continuous readings, daily intermediate measurements were performed. These measurements comprised of the following:

- Air temperature (c)
- Water temperature (c)
- Brash ice temperature profiles (c)
- Salinity profile (c & i)
- Brash ice thickness (i)
- Compressive strength (i)
- Thin sections (i)

Note: where (c) denotes continuous and (i) intermediate measurements.

Before the level ice was broken into brash ice pieces, the level ice properties were measured (according to HSVA's standard procedures), and also during the tests from sections of level ice not used for the brash ice boxes. In addition, thin sections were taken to visualise the crystalline structure and time lapse cameras were used for observations. Illustration of the scheme of tests is shown in Figure 2-2 below.

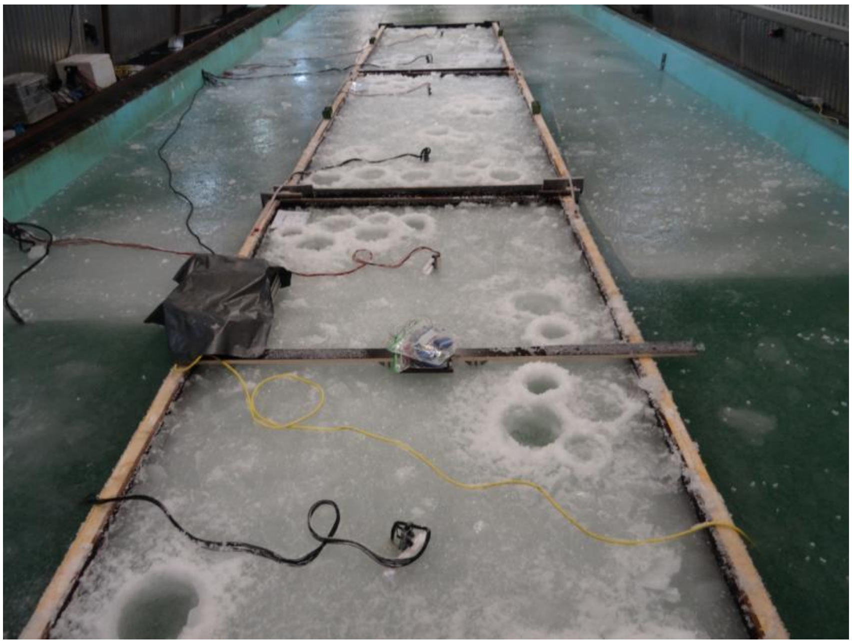

*Figure 2-2. Scheme of brash ice boxes and measurements during the programme with the two sets of temperature sensor positions in each box and also locations of some core samples can be observed at the edges of the boxes.*

## 3. SUMMARY OF RESULTS

To investigate the consolidation behaviour of the brash ice parameters the measured data is briefly analysed and the following provides some results from the tests and short description of the observations.

### 3.1. Temperature

An example of the evolution in temperature profiles is shown in Figure 3-1 below. A clear observation from the tests is that it takes several days for the brash ice temperature (and consolidation) to lower significantly over the depth of brash ice. For full consolidation with significant change of temperature over the entire brash ice depth it is estimated that at least one week is need (brash ice depth of 0.3 m, air temperature abt. -15°C).

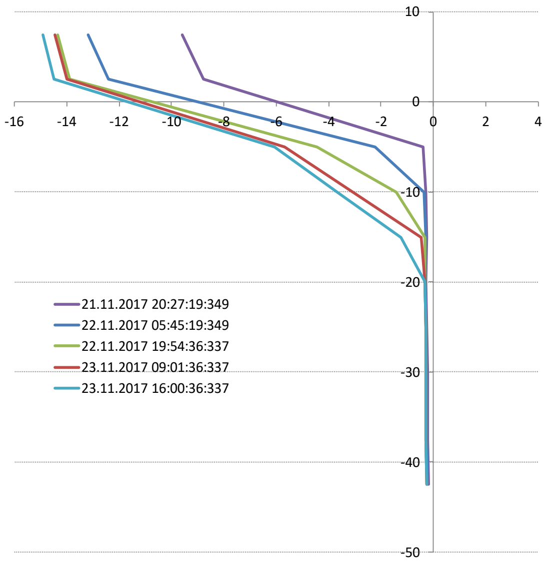


*Figure 3-1. Example of temperature profile evolution with time. Where y-axis is the depth/freeboard height through the ice, in cm, and x-axis is the temperature, in deg. C. The coloured lines show the temperature profile at different times of the testing with progressive freezing of the brash ice.*

## 3.2. Compressive strength

In order to observe the brash ice properties during the tests a series of ice cores and samples were taken from each of the brash ice boxes every day to measure the consolidated ice thickness, salinity and compressive strength. Examples of cores are shown in Figure 3-2. Samples were taken from these cores for compressive testing and in order to differentiate the development of the compressive strength the samples were taken in both vertical and horizontal directions. See Figure 3-3.


*Figure 3-2. Examples of cores taken after 24hrs (left image) and 48hrs (right image). Brash ice pieces frozen on the bottom of the samples can be clearly observed with variation in lower ice surface.*

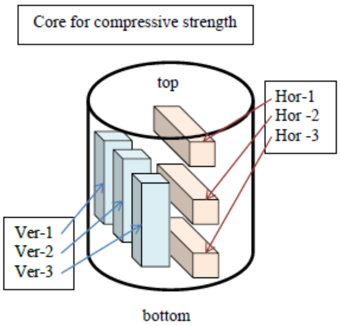

*Figure 3-3. Illustration of cutting scheme for compressive strength (left image) and layout of the samples for compressive strength testing taken from one core (vertical samples on the left side of the image and horizontal samples on the right side of the image).*

The compressive strength of cores from the brash ice boxes showed an increase of strength over time. Results are presented in Figure 3-4 and Figure 3-5 below. In general, the compressive strength in the vertical direction is higher than that in the horizontal direction, and also higher in the top compared to bottom. The brash ice tests with lower salinity was also stronger than those of higher salinity. The rate of strength increases as the brash ice thickness decreases, and also as porosity increases. The results, however, show much variation and scatter reflecting the randomness of brash ice composition and properties.

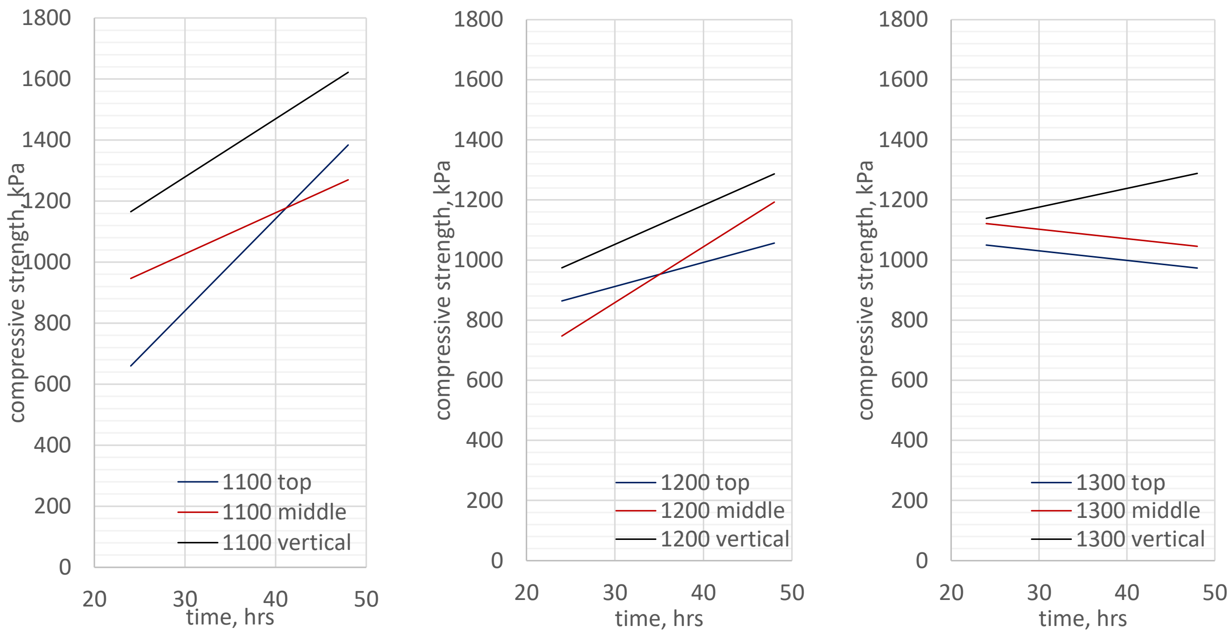


*Figure 3-4. Evolution of the average compressive strength of the brash ice for the first series tests 1100-1300 with low salinity and increasing thickness variation (left to right).*

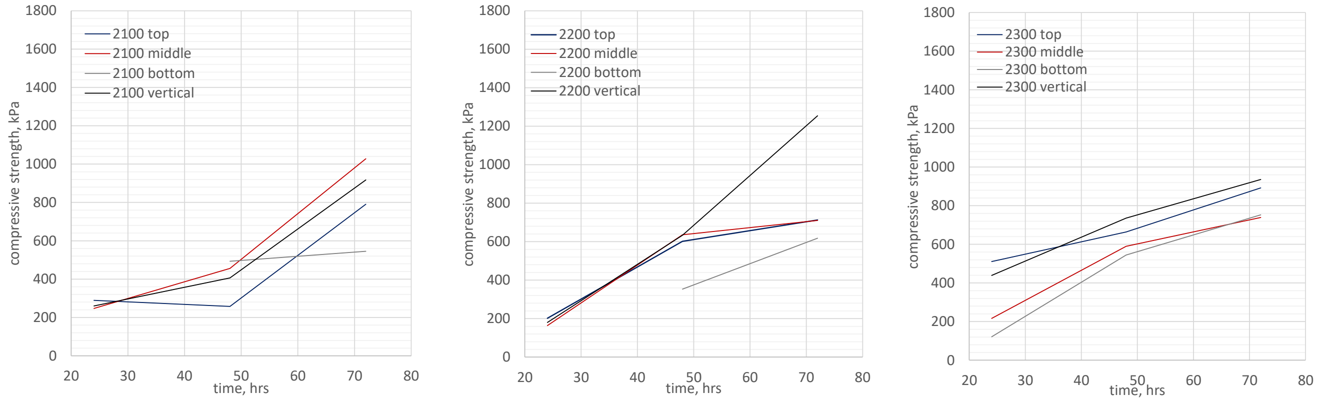


*Figure 3-5. Evolution of the average compressive strength of the brash ice for the second series tests 2100-2300 with high salinity and increasing porosity variation (left to right).*

## 3.3. Salinity content

Brash ice cores were taken daily from the brash ice boxes and the salinity was measured at both the top and bottom of the samples. It took several days for the salinity to change in the top surface of the consolidated brash ice, although the opposite trend is observed for the lower surface which exhibits greater change in the initial stages and less with increasing time. This change is observed in the second series tests which were conducted over longer period, as seen in Figure 3-6 below.

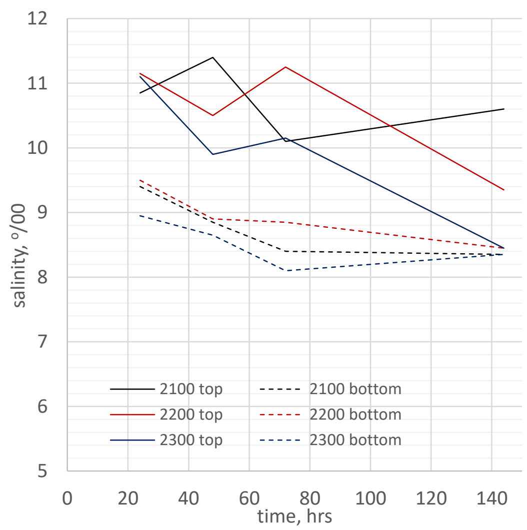


*Figure 3-6. Evolution of the average top and bottom values for salinity of the brash ice test second series 2000 (with porosity variation and a higher salinity content).*

## 3.4. Crystalline structure of brash ice

Thin sections were taken to investigate whether discernible changes in the crystalline structure could be observed in the consolidation of brash ice. In order to observe the development of the crystalline structure of the consolidating brash ice, the thin sections were prepared from cores taken from each box every 24 hrs. The thin sections were taken in horizontal and vertical directions. The sections reflect the random orientation and variations, as shown in Figure 3-7.

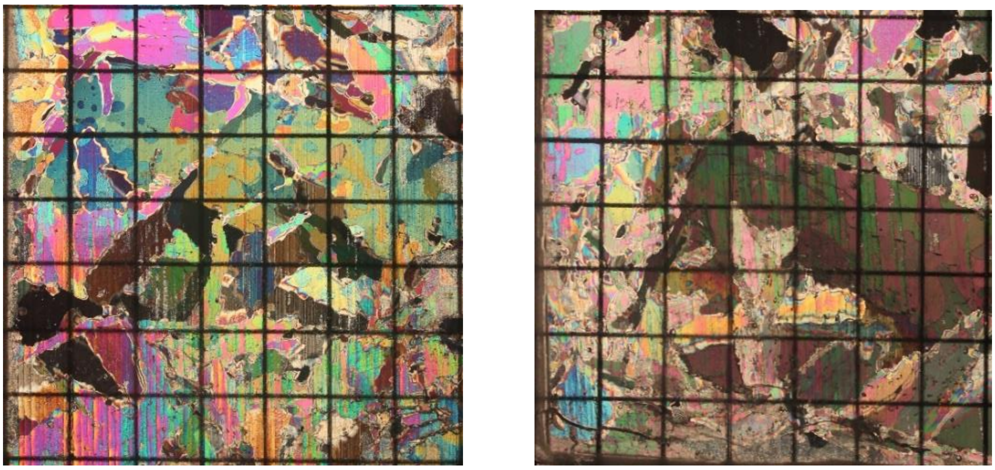

*Figure 3-7. Examples of the thin sections of the brash ice from 1100 series after 24 hrs taken in horizontal direction (left image) and vertical direction (right image).*

## 4. CONCLUSIONS

The properties of brash ice and especially the consolidation process plays an important role in a wide range of design conditions and marine operations, especially in rubble accumulations around offshore structure, ice management and port berthing operations. Experiments were conducted to investigate a range of different parameters, namely brash ice thickness, porosity, and salinity, to better understand the processes. The tests included a series of different measurement techniques and the data acquired has provided an insight into the dynamics of consolidation. Of particular note in the tests is the preparation of controlling the brash ice porosity which turned out to be quite difficult.

The analysis of the data is ongoing, however, some findings are already apparent, such as the length of time required; over several days for consolidation process, and this is reflected in the temperature measurements and also salinity profiles. The process of consolidation also does not appear to be linear and a transient process, the reasons for this are still to be investigated. The results of the compressive strength of the brash ice clearly show a difference in the brash ice top and lower layers as well as in vertical and horizontal directions. These findings provide a better understanding of the consolidation process. Future analysis and investigations in this topic will enable improved safety in design arrangements and operational efficiency.

## ACKNOWLEDGEMENTS

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