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The Physical Characteristics of Consolidated Saline Ice: Results from Ice Tank Experiments

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Abstract

We present results from consolidation experiments on saline ice conducted at the Hamburgische Schiffbau-Versuchsanstalt (HSVA) Large Ice Model Basin (LIMB) in Hamburg, Germany. The aim was to investigate the strength and physical characteristics of freeze-bonds developed in a range of conditions encountered in rafted and ridged sea ice, by employing: 1) free floating ice compared with submerged ice and, 2) the presence or absence of a liquid layer. Stacks of two 1m^2 blocks of saline ice were used: 1) free-floating and submerged beneath the water surface and, 2) with a 3 mm liquid layer and with direct contact between the ice blocks. There were a total of four experiments, each left to consolidate for five days, during which the temperature and salinity evolutions were measured. By the end of the consolidation period the two direct contact experiments had consolidated sufficiently for full cored samples to be taken. Conversely, those experiments that contained a liquid layer were too weak to survive coring, despite an apparent freezing of the brine within the layer deduced via salinity measurements. Cored samples from each experiment were taken, from which salinity profiles were determined. The compressive strengths of samples from the direct contact experiments were also measured and compared to level ice. Both consolidated samples were weaker in compression than the level ice. The sample from the submerged experiment was considerably weaker than the sample from free-floating ice. The observations from the two liquid layer experiments support the necessity to distinguish between thermodynamic and full mechanical consolidation.

1. Introduction

Ridging and rafting are features that arise in regions of compression/shear in the Arctic sea ice cover. Ridge keels and rafted layers both comprise pieces of saline ice separated by liquid sea water which gradually freezes, resulting in bonding between constituent ice pieces and an overall strengthening of the feature in a process known as consolidation. When subjected to wind shear and/or ocean currents, these consolidated features may exert considerable loads on offshore structures or pose hazards to vessels operating in the region. From an engineering perspective, it is therefore necessary that the physical and mechanical behaviour of rafted and ridged sea ice are well characterized throughout the consolidation procedure. Of particular importance are the mechanical properties of the freeze bonds (F.B.s) that form between constituent ice pieces during consolidation as it has been suggested that F.B. strength governs the initial strength of consolidated ice rubble [*Ettema & Urroz* (1989)]. This paper details four experiments conducted to investigate the effect of two factors on the consolidation process: 1) free-floating vs. submersion beneath the water surface and, 2) a 3mm liquid layer vs. direct contact between the ice blocks. These conditions were chosen to cover a range of conditions encountered in rafted layers and ridge keels.

2. Experimental Methodology

2.1 Ice Tank Properties

The experiments were conducted over a four-week period at the Hamburgische Schiffbau-Versuchsanstalt (HSVA) Large Ice Model Basin (LIMB) in Hamburg, Germany, which has dimensions: 78 m x 10 m x 2.5 m and contains NaCl-doped water with a spatially varying salinity ranging between 6-8 ppt. These range of values are considerably lower than typically encountered in Arctic seas, but had the advantage of increasing the freezing temperature, thus expediting the consolidation process. Adjacent to the ice tank lies a cold room containing storage facilities and apparatus to prepare samples and investigate the mechanical and crystallographic properties of the ice. The structure of natural S-type sea ice was replicated by using 'artificial full scale ice', which was grown to a level thickness of approximately 15 cm before the experiments were conducted. The nominal air temperature was approximately -10°C for the duration of the experiments.

2.2 Direct Contact Experiments

The methodology was based on similar consolidation experiments described in *Bailey* (2011). The same lateral dimensions (1 m x 1 m) were used to provide a direct comparison to the results obtained in *Bailey* (2011) and to enable a sufficiently large area for a number of cored samples to be extracted for analyses. Four $1m^2$ blocks were cut from the level ice side-by-side such that a 4 m x 1 m channel was created, after which the blocks were manually stacked. To measure the temperature profiles of the ice blocks over the consolidation period, temperature strings, each containing four Resistance Temperature Detectors (RTDs), were frozen into the centre of each ice block. For the submerged experiment, weights were added on top in addition to a metal framework, which prevented lateral movement of the blocks beneath the waterline. A layer of polystyrene was added between the blocks and the framework to further insulate the experiment from the atmosphere and to prevent conduction between the ice and metal. A summary of the experimental arrangements for the two direct contact experiments is shown in Figure 1.

2.3 Liquid Layer Experiments

Following the completion of the direct contact experiments, the 3 mm liquid layer experiments were prepared. By this time, the level ice had reached a thickness of approximately 25 cm. The experimental set-up closely followed the direct contact experiments shown in Figure 1, but with two necessary alterations. Firstly, to provide the gap for the liquid layer, 3 mm thick Perspex spacers were frozen onto the surface of the lower ice blocks prior to assembly. Due to issues with the logging, the RTD strings could not be used in these experiments. The temperature evolution of the liquid layers was monitored using individual K-type thermocouples. For the submerged experiment, metal framework, polystyrene insulation and weights were added, as per the direct contact methodology.

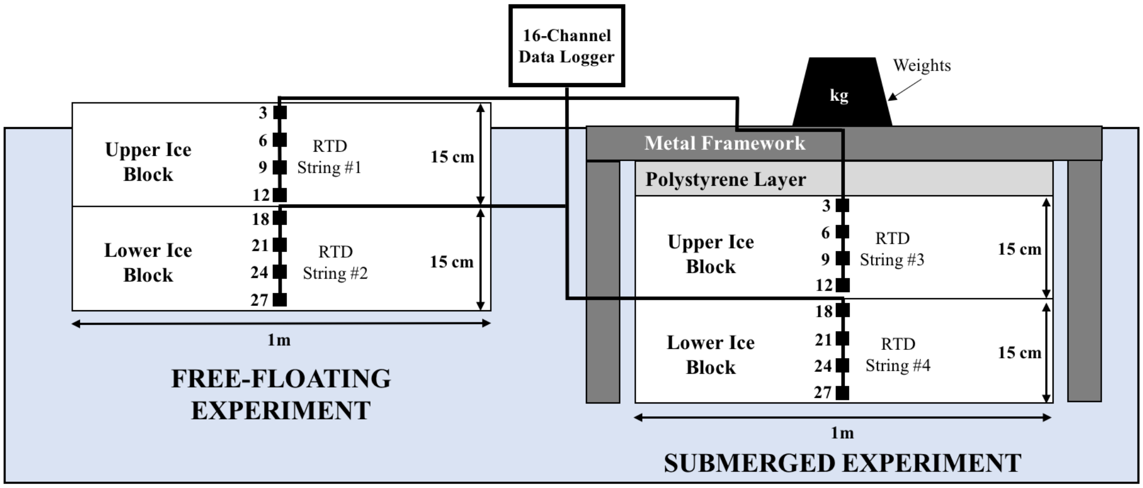

Figure 1. Experimental arrangements for the free-floating and submerged experiments in direct contact. The liquid layer experiments followed the same basic arrangement, but with the changes described in-text. The numbers next to each RTD represents the depth in centimetres from the top surface of the upper ice block.

3. Results

3.1 Consolidation Time

Each experiment was left to consolidate for approximately five days. The state of consolidation was monitored using a combination of coring and drilling through the upper ice blocks to the F.B. layers. All cores were extracted using a 7 cm diameter auger. The extent of the consolidation was primarily deduced from the resistance experienced when drilling and the physical state of the subsequent cores. This was further investigated by drilling through to the F.B. layer and extracting brine using a pipette. The F.B. layer was considered fully frozen when brine could no longer be extracted. This was done for the two free-floating experiments, but was not possible in the submerged experiments.

The salinity of the brine measured in the liquid layers of both free-floating experiments increased over the initial consolidation period. At the beginning of the experiments, the salinities were the same as the surrounding water. After approximately one day, the salinities of both F.B. layers had increased to around 18 ppt. After 36 hours, it was no longer possible to extract brine from the F.B. layer in the free-floating direct contact experiment. For the free-floating liquid layer experiment, brine could no longer be extracted after 96 hours. After five days, the direct contact experiments had consolidated sufficiently for full cored samples to be taken. However, after the same amount of time, no cores from the liquid layer experiments remained intact, indicating that consolidation had not been reached.

3.2 Temperature Evolutions

Due to the previously mentioned issues with the logging, only the first 1600 minutes of the consolidation phase was measured. Furthermore, the temperature data over this time period was intermittent as the software crashed multiple times. Temperature profiles at different times over the first 1600 minutes of consolidation are shown in Figure 2. It should be noted that three of the RTD probes measured anomalously low temperature readings. This originated from instrumental error, as these RTDs were calibrated three months earlier than the others. These anomalous temperature readings are not shown in the plots in Figure 2. The temperature evolutions measured by the thermocouples in the liquid layer experiments are plotted in Figure 3.

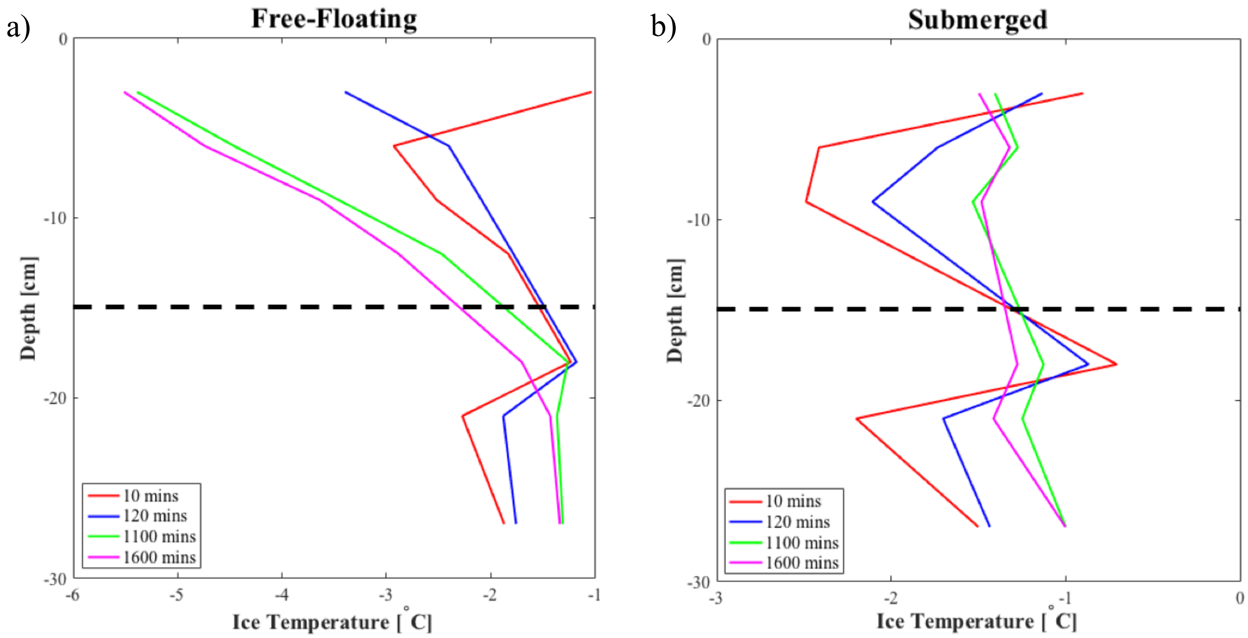

Figure 2. Temperature profiles at different times over the first 1600 minutes of the consolidation period for a) free-floating direct contact experiment and b) submerged direct contact experiment. The black dotted line denotes the approximate location of the F.B. layer.

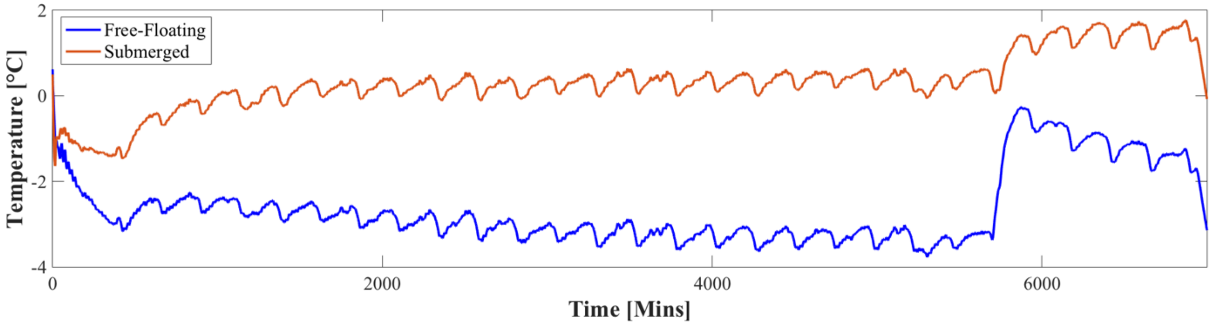

Figure 3. Temperature evolution in time of the 3mm liquid layers in the two liquid layer experiments. The increase in temperatures measured just prior to 6000 minutes is due to a corresponding increase in the air temperature.

As shown in Figure 2, the temperature profiles in both the free-floating and direct contact experiments gradually become more linear as heat is redistributed throughout the thickness of the two ice blocks. However, 1600 minutes was not enough time for the temperature profiles to become fully linear. The free-floating experiments decrease in temperature at a faster rate than the submerged experiments due to exposure to the colder atmosphere, resulting in a greater amount heat conduction away from the ice compared to the submerged experiments. The temperature measured in the liquid layer of the submerged experiment remained at around the freezing point of the tank water, which ranged between -0.3°C and -0.5°C, depending on the exact salinity. This suggests that the liquid layer did not fully freeze over the consolidation period, supporting the observations that were made when coring.

3.3 Salinity Profiles

Salinity profiles were taken of the level ice and each consolidation experiment. It should be noted that even though the liquid layer experiments had not fully consolidated, it was still possible to take salinity profiles. Cores were cut into sections and melted down in plastic containers, and the salinity of the resulting brine measured using a salinity meter. The results are plotted in Figure 4.

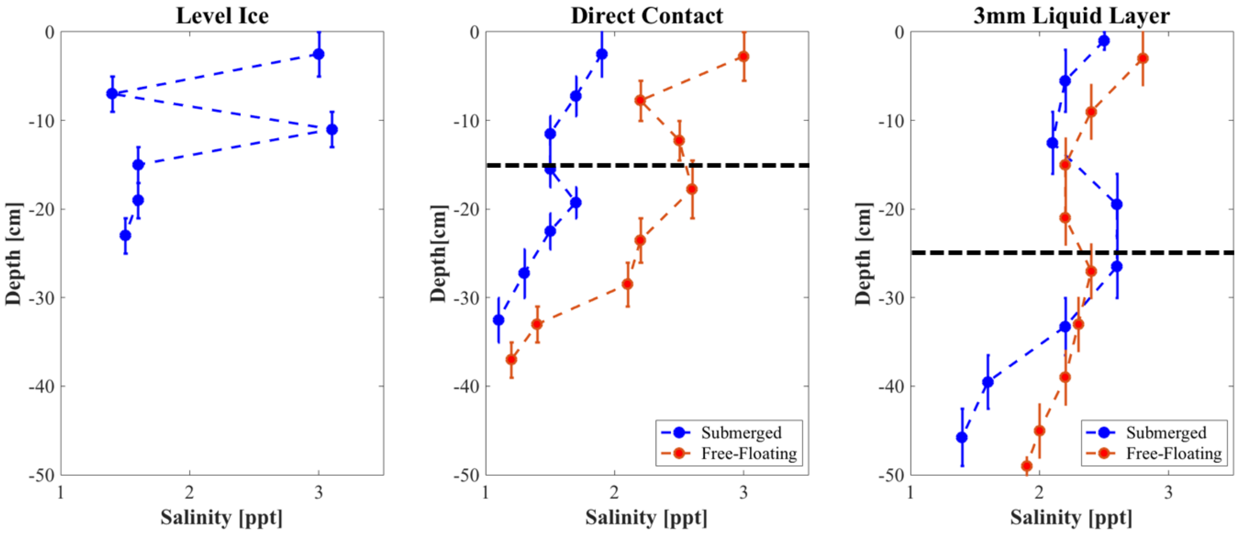

Figure 4. Salinity profiles of the level ice and two direct contact experiments. The dotted black lines indicate the approximate positions of the F.B. layers. The vertical error bars denote the thickness of each section of the core

The salinity profile of the level ice differs from the expected C-shape typical of young sea ice, which has been attributed to brine drainage from sections of the core during extraction, transportation and preparation. This is supported by observing the salinity profiles from each experiment, which all exhibit approximately C-shaped distributions in the upper ice blocks. In each consolidation experiment, there is a peak in salinity at the approximate locations of the F.B. layers, which is consistent with the observations from drilling. The salinity in the lower ice block in each experiment gradually decreases with thickness in a relatively linear fashion. In theory, the salinity at the bottom of the lower ice block should exhibit a peak from newly formed, more saline ice. This disparity has been attributed to brine drainage from the lower sections of the cores during extraction.

3.4 Ice Structure

Any cores that remained intact were imaged under lighting provided by a polariscope. This gave an indication of the position and structure of the F.B. layer and any other visible features present in the samples. Photographs of typical intact cores from the two direct contact experiments are shown in Figure 5. There was an obvious 1cm thick layer in the free-floating sample (Figure 5a), which we believe corresponds to the F.B. layer. For the submerged ice (Figure 5b), the exact position and structure of the F.B. layer was ambiguous, due to the presence of an approximately 7cm thick high porosity band towards the centre of samples.

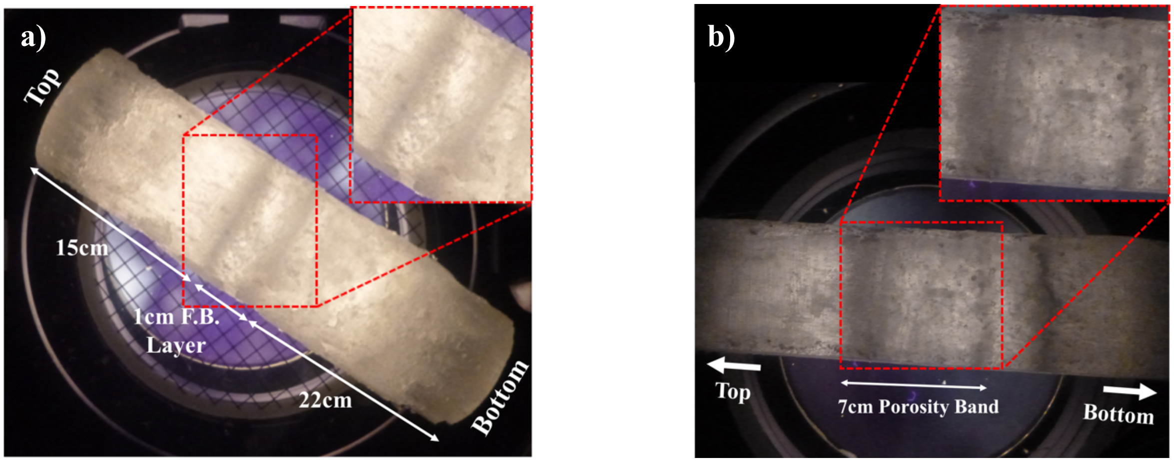

Figure 5. Samples illuminated under polariscope from a) free-floating direct contact experiment and b) submerged direct contact experiment.

3.5 Compressive Strengths

The compressive strengths of the consolidated floes in the direct contact experiments were measured and compared to level ice using a 10 kN uniaxial load frame situated in the cold room. Due to the relatively low maximum load that could be applied by the uniaxial frame, the cored samples were cut to a smaller square cross-sectional area of 4 cm x 4 cm using a band-saw. The samples were orientated such that the F.B. layer was perpendicular to the loading axis. All tests were performed at a constant loading rate of approximately 5 mms^{-1}. Three compression tests were conducted – one for the level ice and each of the direct contact experiments. Relevant parameters for each sample tested under compression are given in Table 1.

Table 1. Parameters for the uniaxial compression tests: air temperature (T_{air}), ice temperature during test (T_{ice}), bulk ice salinity (S_{bulk}), maximum load (F_{max}) and compressive strength (σ)

	Length [cm]	T_{air} *[°C]*	T_{ice} *[°C]*	S_{bulk} *[ppt]*	F_{max} *[kN]*	σ *[MPa]*
Level Ice	10	-8.0	-6.6	-	4.65	2.91
Free-Floating	10	-11.2	-4.2	1.3	2.78	1.74
Submerged	13	-8.9	-10.5	-	1.11	0.70

The level ice was strongest, with a measured strength of $\sigma_{\text{level}} = 2.91$ MPa. The free-floating direct contact sample was next strongest, but was 60% the strength of the level ice. Despite possessing a lower ice temperature, the submerged direct contact sample was considerable weaker: 24% the strength of the level ice, and 40% the strength of the free-floating sample.

4. Discussion

The initial thickness of the ice blocks in the liquid layer experiments were approximately 10 cm thicker than in the direct contact experiments, which acted to increase the time for heat diffusion through the thickness of the ice blocks. Additionally, the presence of a thicker liquid layer meant a greater amount of total heat transfer to the surrounding ice would have been required for full freezing. Increased consolidation time with liquid layer size has been observed in previous thermodynamic models [*Bailey et al.* (2010)] and in the laboratory [*Bailey et al.* (2012)].

Increased salinity of the F.B. layer over the initial consolidation period has been previously documented [*Marchenko & Chenot* (2009), *Bailey et al.* (2012)] and results from both brine drainage from the upper block and salt rejection during freezing. The salinity of the liquid layer can provide an indication of the state of consolidation. *Bailey et al.* (2012) distinguish between thermodynamic consolidation: where the ice has physically bonded, and mechanical consolidation: where the F.B. strength stabilises and the salinity of the layer becomes constant. Using these definitions, it may be concluded that after 96 hours the free-floating liquid layer experiment may have thermodynamically consolidated, since no brine could be extracted from the liquid layer. However, after five days the F.B.s were too weak to survive coring, suggesting that the strength had not yet stabilised, and thus mechanical consolidation had not been reached.

The F.B. layer in the free-floating experiment in direct contact measured approximately 1cm, which was thicker than expected. *Bailey* (2011) also found a thicker F.B. layer (around 2 cm for an anticipated 3mm liquid layer) in the similar HSVA consolidation experiments which was attributed to the twisting of thermistor cables within the liquid layer, which acted to increase the gap above the anticipated 3mm thickness. It is possible that something similar may have occurred in the direct contact experiments. Indeed, the cables for the lower RTD strings were attached to Perspex and frozen onto the top surface of the lower ice blocks prior to assembly, which may have acted to increase the thickness of the gap between the two ice blocks. The high porosity band present in the submerged direct contact samples probably corresponds to a 7-8 cm thick brine porous layer at the base of the level ice, which was revealed when taking vertical thin sections.

The free-floating direct contact experiment was essentially a rafted ice set-up, and thus it is suitable to compare the strength result to previous studies on the compressive strength of rafted sea ice. *Jizu et al.* (1991) note that the strength of rafted ice is considered to be 10-20% weaker than level ice, which is still proportionately stronger than measured in this experiment. However, *Poplin & Wang* (1994) found the average compressive strength of vertically orientated rafted sea ice to be approximately 40% the strength measured for landfast sea ice. The submerged ice was considerably weaker in compression than the other two types of ice. This was true even though the ice temperature under testing was several degrees colder than the other two samples. The low compressive strength may be due to the presence of the high porosity band that constituted a large proportion of the sample. The compressive strength of columnar saline ice is found to decrease with increasing total porosity [e.g. *Moslet* (2007)]. It is interesting to note the different failure mechanisms of the samples under compression. The level and free-floating samples exhibited multiple axial splitting, typical of saline ice loaded vertically under unconfined uniaxial compression at high strain rates [e.g. *Kuehn & Schulson* (1994), *Sammonds et al.* (1998)]. In contrast, the submerged ice failed catastrophically within the top section of the sample, above some point in the high porosity layer. The different failure mode observed in the submerged sample may have occurred because the microstructure within the porosity band was different from the surrounding columnar level ice.

5. Conclusions

Consolidation experiments were performed at the HSVA LIMB to investigate the effect the effect of an atmospheric heat flux and liquid layer on the consolidation of two 1m^2 blocks of saline ice. The physical and mechanical properties of the ice in each experiment were measured and compared to level ice. After five days, the experiments in direct contact had mechanically consolidated, but the liquid layer experiments had not, despite reaching a state of apparent thermodynamic consolidation in the case of the free-floating experiment.

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