POAC'11
Montréal, Canada

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

POAC11-019

EXPERIMENTS ON THE RELATION BETWEEN FREEZE-BONDS AND ICE RUBBLE STRENGTH PART II: FREEZE-BOND EXPERIMENTS AND COMPARISON WITH NUMERICAL SIMULATIONS

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ABSTRACT

A series of experiments with freeze-bond strength and ice-ice friction have been carried out in the NTNU ice laboratory in combination with shear-box tests on ice rubble. Freeze-bonds were tested with the same confinement during formation and testing (classical configuration) and with opposite confinement (inverted configuration). In the first case the results were similar to those of previous works. In the tests with inverted configuration it was difficult to see any clear trend of shear stress vs. normal pressure. The rubble freeze-bond tests produced a negative friction angle but we suspect that this is due to softening behaviour while adding the confinement prior to testing. The freeze-bond seems to be important for the continuum behaviour of ice rubble, but probably somewhat less important the older the rubble is. By combining the freeze-bond strength and ice-ice friction measurements a cohesion softening behaviour was derived just as in previous works. By comparing the test with long and short submersion times with numerical simulations published earlier it seems that the freeze-bond area is a key parameter in the estimation of continuum rubble properties. The softening cannot explain the differences between the experiments and the simulations. Finally it seems to be a fairly good correspondence between the numerical works and our physical experiments with a similar configuration.

1. INTRODUCTION

Freeze-bond failure is thought to be the mechanism responsible for the initial failure of ice rubble (Ettema and Urroz, 1989, Surkov and Truskov, 1993, Surkov et al., 2001, Shafrova et al., 2004, Liferov, 2005) which could give the peak load during rubble-structure interaction (Liferov and Bonnemaire, 2005). Several authors have studied the freeze-bond strength using different set-ups and experimental methods (Shafrova and Høyland (2008) – S&H, Marchenko and Chenot (2009) - M&C, Ettema and Schaefer (1986) – E&S and Repetto-Llamazares et al. (2011a) - RL). Given the same type of ice, the main parameters affecting the freeze-bond strength are the normal confinement and the submersion time. There are two different types of normal confinements affecting the freeze-bond strength: the confinement during freeze-bond formation and during mechanical testing. But it is not known how each of these affects the freeze-bond strength.

In earlier investigations the confinement during formation (σ_{FB}) and during testing (σ_{TEST}) have been equal and simply called confinement. This is not necessarily the case in nature, and the main question is whether the confinement in the rubble during a ridge-structure interaction will change substantially prior to freeze-bond failure or not. If the interaction scenario is so that basically shear stress is applied, then testing with $\sigma_{FB} = \sigma_{TEST}$ will be reasonable. If not, the situation becomes more complicated since each layer of the ridge will constitute its own material properties.

In a shear box the boundary conditions are better known than in nature and the results are easier to analyze. Shafrova (2007) performed numerical simulations of a 2D shear box test with a similar configuration as the one used in our experiments (Table 1). She used a pseudo-discrete continuum model where the ice blocks were connected with contact elements. The elements constituting the ice blocks and the contact elements were given different mechanical properties and she examined the overall capacity of the shear box (rubble strength) for small strains (implicit integration).

Table 1. Non dimensional numbers used by Shafrova (2007) and corresponding values of our shear box experiments. Ratio of the shear box length and the shear box height (L_{SB}/h_{SB}), ratio of the length of the ice blocks and the thickness of the ice blocks (L_b/h_b) and the length of the shear box divided by the thickness of the ice blocks (L_{SB}/ h_b).

	L_{SB}/h_{SB}	L_b/h_b	L_{SB}/h_b
Shafrova (2007)	2	3.3	12.7-23.3
Serré et al. (2011)	1.5	2.8	28.6

The freeze-bond tests presented in this paper were designed with two main purposes:

1) To study the relation between freeze-bond shear strength and rubble shear strength.

2) To study what happens when the normal confinement during freeze-bond formation is different than during freeze-bond mechanical testing.

2. EXPERIMENTAL PROCEDURE

2.1 Set up: Freeze-bond shear device

The experimental set-up was designed according to the description of the improved experimental set up of 2009 experiments presented in Repetto-Llamazares et. al (2011a) with the dimensions adjusted to fit the blocks used in the shear box experiment. A simplified draw of the set-up is presented in Figure 1.

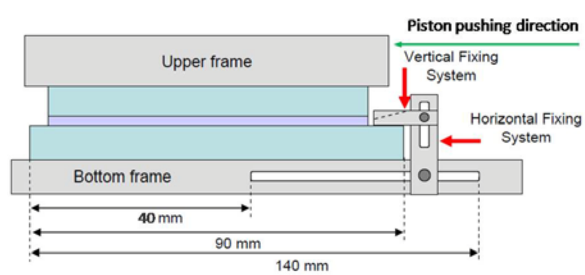


Figure 1. Sketch of the experimental set-up used to measure freeze-bond strength.

2.2 Experimental Method

Three different freeze-bond experiments were designed and conducted; a) *traditional* with *classical configuration*, b) *traditional* with *inverted configuration* and c) *rubble-freeze-bond*. In all 3 set-ups we used two different confinements (High – 2 kPa and Low - 0.4 kPa) and two submersion times (Short 0.17 hr and Long 20 hr), see Table 2 for an overview. All samples were submerged in water with a salinity of 8 ppt, the same salinity as the water the ice was grown from. Each data point was calculated as the average ± standard deviation of 3 to 5 experiments.

Table 2. Test matrix of the different freeze-bond strength experiments. Normal confinement used during freeze-bond formation (σ_{FB}), normal confinement used during freeze-bond mechanical testing (σ_{TEST}), submersion time (Δt) and number of samples tested under the same conditions (n).

Exp.		Test Name	σ_{FB} [Pa]	σ_{TEST} [Pa]	Δt [hr]	*N*
Classic	classic	High_High_Long	1900	2040	20	3
		Low_Low_Long	350	480	20	3
		High_High_Short	1900	2040	0,17	4
		Low_Low_Short	350	480	0,17	4
	iniverted	High_Low_Short	1900	480	0,17	4
		Low_High_Short	350	2040	0,17	4
		High_Low_Long	1900	480	20	2
		Low_High_Long	350	2040	20	3
rubble freeze-bond		High_Short	----	2950 ± 370	0,17	5
		Low_Short	----	715 ± 90	0,17	5
		High_Long	----	3010 ± 390	20	4
		Low_Long	----	690 ± 80	20	4

In the traditional tests individual freeze-bonds were submerged and subsequently tested. In the classical configuration the confinements during formation and testing were equal ($\sigma_{FB} = \sigma_{TEST}$ as in E&S and RL). In the inverted configuration the confinements were not equal but opposites. The original ice pieces were approximately 2 cm thick and 4 cm wide, and the length was about 6 cm (upper block) and 9 cm (bottom block, see Figure 1). The piston velocity was constant during each test (the average /standard deviation / minimum and maximum were respectively 2.1 mm/s / 0.7 mm/s / 0.9 mm/s and 3.45 mm/s).

The *rubble-freeze-bond* experiments were done using freeze-bonds that were formed in similar conditions than those found in the shear box experiment, by extracting the freeze-bonds from a box containing rubble of similar characteristics to the rubble used in the shear box tests (Figure 2). The piston velocity was constant during each test (the average /standard deviation / minimum and maximum were respectively 2.2 mm/s / 1.2 mm/s / 0.45 mm/s and 3.6 mm/s).

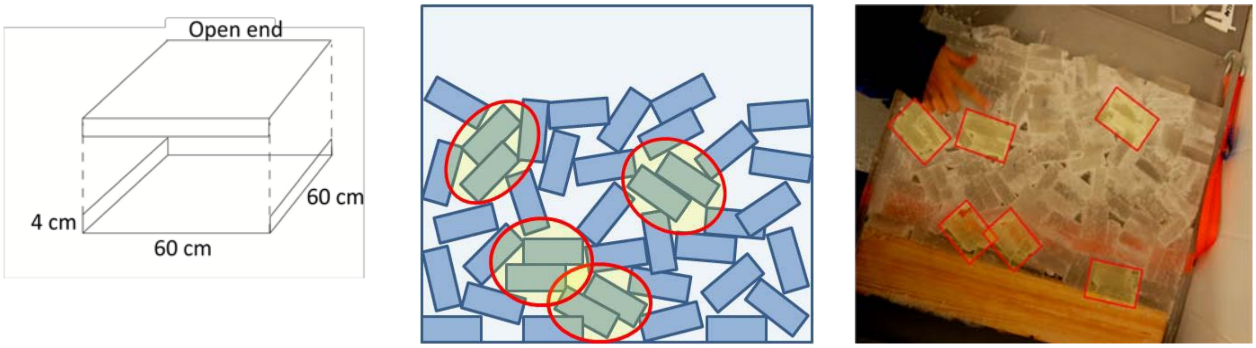


Figure 2. Box used for making freeze-bonds equivalent to those present in the shear box tests and examples of freeze-bonds used in the rubble-freeze-bond tests.

3. RESULTS

Figure 3 shows a typical force-time diagram. The results were found in the same way as in Repetto-Llamazares et al. (2009).

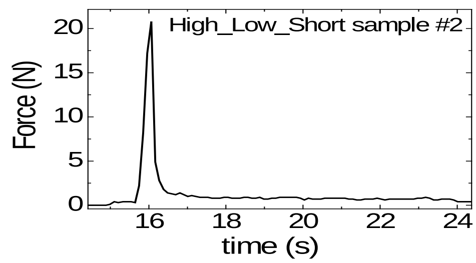


Figure 3. typical force-time trace from freeze-bond testing.

3.1 Freeze-bond strength

Figure 4 shows the results of the results from the traditional tests and Figure 5 those from the rubble freeze-bond tests.

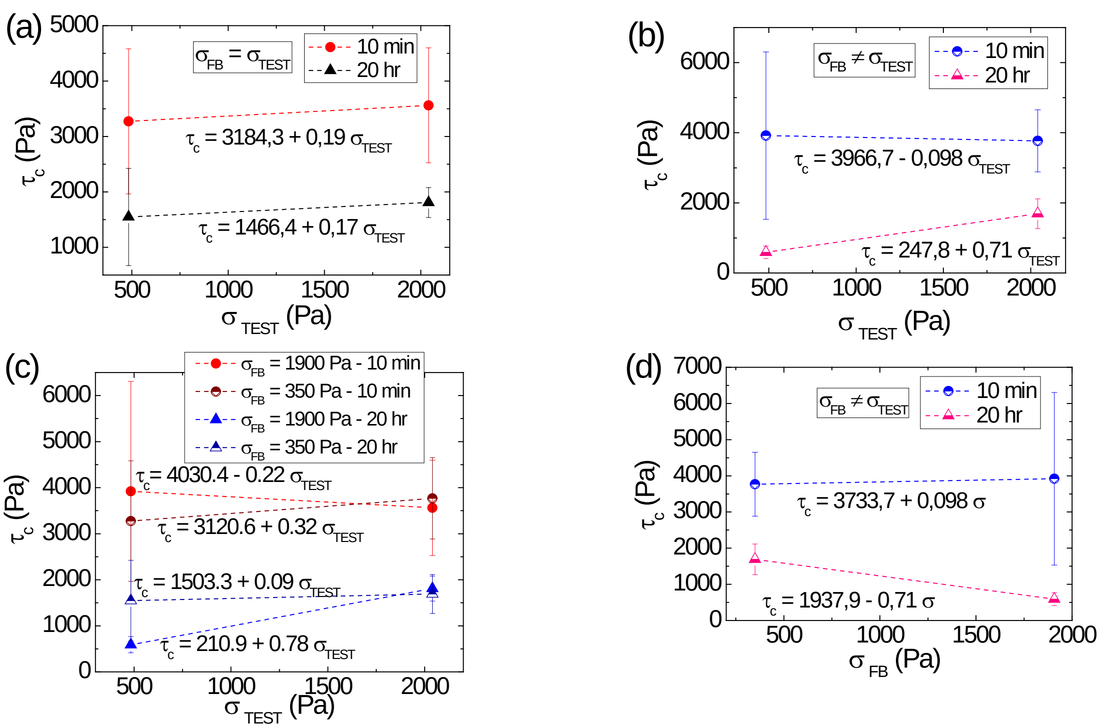


Figure 4. Results obtained from the freeze-bond traditional tests as plots of freeze-bond shear strength vs. normal confinement. Error bars = ± Standard deviation. (a) Classic configuration,

where the normal confinement during freeze-bond formation (σ_{FB}) was the same as during the mechanical testing (σ_{TEST}). (b) Inverted configuration, where σ_{TEST} is the opposite of σ_{FB} (data plotted as function of σ_{TEST}) (c) Data from the inverted and classic configuration used to build data sets with constant σ_{FB}. (d) Inverted configuration (same results as in (b)) plotted as a function of σ_{FB}.

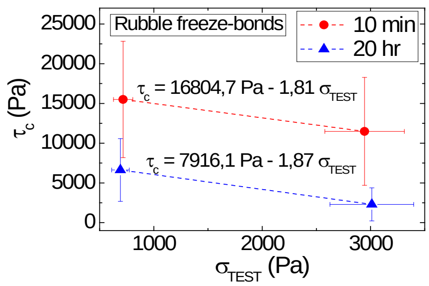


Figure 5 Results obtained from the rubble-freeze-bond tests as freeze-bond shear strength vs. normal confinement during mechanical testing. Error bars = ± Standard deviation.

3.3 Ice-ice friction after freeze-bond failure

The friction force after freeze-bond failure was studied as in Repetto-Llamazares et al. (2011b). In their paper the friction force 1 second after failure and after stabilization was analyzed. In the present work, the force 0.3 s after failure was analyzed since it corresponds to a similar relative displacement between the ice blocks (given the different piston velocities used). All tests gave a non-zero cohesion and a positive friction angle (see Figure 6).

4. DISCUSSION

4.1 Freeze-bond Strength

The effect of the submersion time was clear in all tests, the strength for Δt = 0.17 hr was 2 to 4 times higher than the one for Δt = 20 hr. Repetto-Llamazares et al. (2011a) also found higher strengths for shorter submersion times for Δt higher than 5 minutes (decreasing part of the Δt *vs.*σ bell-shaped curve). The strength for 20 hr was comparable with those of RL, but our short submersion strengths were lower in general than those of RL (3-4 kPa vs about 12 kPa). We do not know why, but it is probably related to the quality of the ice surface.

The freeze-bond strength versus the confinement gave different trends. In the Traditional set-up with classical configuration we got results similar to those of E&S and RL with positive friction angles. In the traditional with inverted configuration the trend was unclear, and in the Rubble freeze-bonds the results indicate negative friction angle. We do not know the reason for this, but we think that in the experiments where the samples were unloaded and reloaded or when $\sigma_{FB} < \sigma_{TEST}$ the application of the confinement prior to testing could have broken the freeze-bonds and softening might have occurred. If this was the case, we never measured the real strength of the freeze-bond, but only a residual strength.

An interesting difference between the Traditional and Rubble freeze-bond experiments is that the strength of the rubble freeze-bonds were about 3 times higher, for both high and low submersion times. This could be due to a lower oceanic flux because of the surrounding ice in the rubble freeze-bond experiments. A lower oceanic flux means that more of the initial cold energy stored in the blocks can be used to form the freeze-bonds (Høyland, 2007). Having in mind that the rubble design was in 2D, we conclude that the strength of freeze-bonds created inside a 3D rubble field will be more than three times higher than the strength of individually made freeze-bonds since the insulating effect will be stronger in a 3D configuration.

From our results it is seen that if we cannot assume that the freeze-bonds fail under the same confinement that they were created, the validity of the Mohr Coulomb model is not clear and this should be study further using bigger ranges of σ_{TEST}.

4.2 Ice-ice friction after freeze-bond failure

The ice-ice friction behaviour mostly corresponded to what RL measured. However in the present experiments the friction was higher for samples with short submersion times than with long submersion times, which is opposite to RL's results. This can be due to the different quality in the ice-block surfaces used in both experiments. From a visual inspection the ice used in our tests was smoother than the one used by RL.

A last point to mention is that the ice-ice friction after freeze-bond failure will only be of use for Phase 1 of rubble failure since from the results presented in Part I it was observed that in Phase 2 the rubble with longer submersion times had higher strengths than the rubble with short submersion times. Apparently for Phase 2 the friction that dominates failure is the one caused by the slush grown between blocks rather than the friction after freeze-bonds failed.

4.3 Evolution of Mohr-Coulomb parameters

From the linear fitting of the shear stress-confinement data (τ-σ) and the subsequent derivation of Coulomb-Mohr parameters (c and φ) for different times after failure (t-t_{FAIL}, where t_{FAIL} is the time at which the peak force was recorded) Figure 6 was constructed for both the *classical* and the *inverted* configuration in a similar way as Repetto-Llamazares et al. (2011b) did. The figure shows a cohesion softening and that it was stronger for short submersion times just like RL found. However, this study gave opposite friction angle development than RL found. This may be due to different ice surfaces. The ice surface probably plays a role in freeze-bond formation, freeze-bond strength and subsequent ice-ice friction but we have not studied this yet.

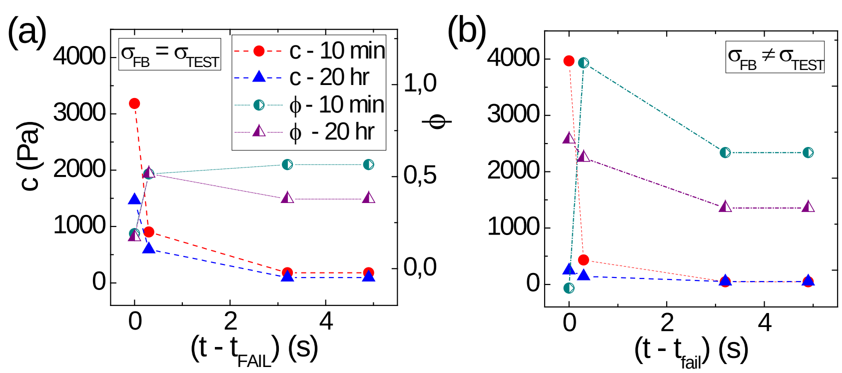


Figure 6. Curves showing the evolution of c and ϕ vs. time after failure (t-t_{fail}, where t_{fail} is the time at which the peak forces was recorded). (a) Classic configuration (b) Inverted configuration.

4.4 Rubble strength in Phase I and freeze-bond strength

In general both the rubble strength measured in the shear box test and the freeze-bond strength were higher for the short submersion times.

Let us use τ_{SB} for the rubble strength in Phase I (as described in Part I of the publications) and examine the ratio of the rubble strength to the critical rubble-freeze-bond stress τ_{FB}/τ_{SB}. Table 3 shows this ratio for our two submersion times and for the simulations of Shafrova (2007). We have used normal confinement of 1.5 kPa (being this half the High normal confinement used).

Table 3. Ratio of the critical rubble freeze-bond stress (τ_{FB}) and the rubble strength (τ_{SB}) for the different submersion times used in our experiments (Δt) and for the numerical simulations by Shafrova (2007).

	Δt = 10 min	Δt = 20 hr	Shafrova (2007)
τ_{FB}/τ_{SB}	1	0.5	3.5

It shows that in order to maintain the same rubble strength Shafrova needed 3.5 – 7 times higher freeze-bond strength than in our experiments. In other words the freeze-bond strength was more important in her simulations than in our experiments. The table also shows that the importance of the freeze-bond strength decreased with increasing submersion time. Let us in turn discuss how a) the areal size (length in 2D) of the freeze-bonds, b) the softening (as given in Figure 6), c) the ratio of the strength of the original ice blocks to the freeze-bond strength (τ_{IB}/τ_{FB}) and d) the elastic properties of both the original ice and the freeze-bonds affect the measured/predicted rubble strength.

The freeze-bond area (A_{FB}) probably increased with increasing submersion time in our experiments (see Figure 16 in Part I). Several years of field investigations into ridge properties make us believe that this is a general truth. Shafrova (2007) used field data from ridge sails to estimate A_{FB} (Shafrova and Høyland, 2008a), and since less freeze-bonds develop in the sail it is reasonable that A_{FB} was somewhat underestimated by Shafrova (2007). More precisely it is the ratio of the freeze-bond area to the shear box area that gives the effect so that a smaller ratio needs to be compensated by larger freeze bond strength to get the same rubble strength (force divided by shear box area).

The freeze-bond softening is the second phenomenon that should affect the freeze-bond/rubble strength ratio. Since not all the freeze-bonds reach their strength (initial failure surface) at the same time a softening behaviour of the freeze-bonds should increase τ_{FB}/τ_{SB}. Shafrova (2007) used a perfect-plastic material, that is no softening, and from this point of view she should have needed a smaller τ_{FB}/τ_{SB}. in other words the softening cannot explain the difference between her simulations and our experiments. However, the freeze-bond softening was less for Δt = 20 hr, and this corresponds with the lower τ_{FB}/τ_{SB}.

The ratio of the strength of the ice blocks to the strength of the freeze-bonds could also affect τ_{FB}/τ_{SB}. If the freeze-bonds had comparable strength to that of the ice blocks, the inelastic behaviour of the ice blocks would contribute significantly to the rubble strength and a variation of the freeze-bond strength would be of lesser importance. Shafrova (2007) multiplied the cohesion and friction angle of the ice blocks with a factor (0.09 average value from her experiments, Shafrova and Høyland, 2008b) and obtained the freeze-bond properties. Our measured properties (See Part I) give a ratio of cohesions of about 0.03 for both *Short* and *Long* submersion times and cannot explain the lower τ_{FB}/τ_{SB} in our tests.

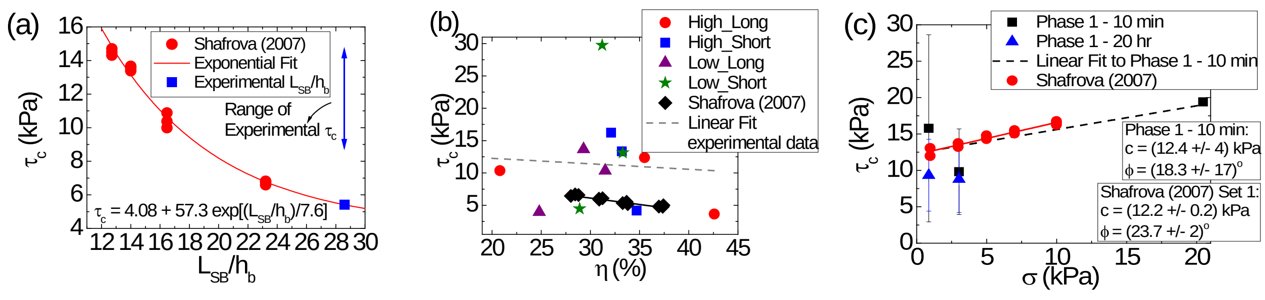
The elastic properties will also affect the rubble strength, but little is known both about the elastic properties of freeze-bonds and about those of submerged ice. Repetto-Llamazares et al. (2011b) investigated and concluded that the elastic shear modulus of the freeze-bonds is small compared to original ice (1-3%). In a material that is both anisotropic and heterogeneous, different elastic properties affect the overall strength. The stiffness (elastic modulus) of the strongest material governs the elastic strain in the weaker material. The higher elasticity of the stronger material, the higher force required to produce the same elastic strain in the weaker material, and consequently gives a higher overall strength. Shafrova used the same elastic properties for both the ice blocks and the freeze-bonds whereas we believe that our ice blocks were much stiffer than the freeze-bonds.

As a summary the freeze-bond area and the elastic properties are important and help in explaining the different τ_{FB}/τ_{SB} ratios. The softening only helps in explaining the difference in between our experiments but should have given an opposite effect on τ_{FB}/τ_{SB} for the simulations.

Let us continue to compare our results with those of Shafrova (2007). In Figure 7 we have plotted her simulations and our experiments for the rubble strength as a function of L_{sb}/h_b, porosity (η) and confining stress (σ). The rubble strength as a function of L_{sb}/h_b shows that our results were higher than the predicted by the numerical simulations. The extrapolation of Shafrova's simulations to our experimental L_{sb}/h_b shows (as discussed in Part I) that our shear box was smaller than one representative volume element (RVE).

The experimental rubble strength as a function of porosity doesn't give a clear trend. This could be because too many variables are mixed into the figure. However if we skip *Low_Long_3* that behaved differently than the two other *Low_Long* tests, all the 4 combinations of *High*, *Low*, *Short and Long*, decreased with increasing porosity.

Shafrova found increasing rubble strength with increasing confinement (σ), but with a decreasing friction angle for increasing σ. In our experiments the only clear trend was between the Short_Extra_High and the other tests where a positive friction angle was found.



Figures 7. Shear strength of rubble as function of the ratio between the shear box length (L_{SB}) and the block thickness (h_b) in (a), as function of the rubble porosity (η) in (b) and as function of the normal confinement (σ) in (c). The figures compare values extracted from Shafrova (2007) with values from or experiments. Error bars = ± Standard deviation.

5. CONCLUSIONS

A series of experiments with freeze-bond strength and ice-ice friction has been carried out in the NTNU ice laboratory in combination with shear-box tests on ice rubble. Freeze-bonds were tested with the same confinement during formation and testing (classical configuration) and with opposite confinement (inverted configuration). In the first case results were similar to those from Ettema and Shaefer (1986) and Repetto-Llamazares (2011a). In the tests with inverted configuration it was difficult to see any clear trend of shear stress vs. normal pressure. The rubble freeze-bond tests produced a negative friction angle but we suspect that this is due to softening behaviour while adding the confinement prior to testing.

The freeze-bond seems to be important for the continuum behaviour of ice rubble, although it probably becomes less important the older the rubble is.

By combining the freeze-bond strength and ice-ice friction measurements a cohesion softening behaviour was derived as done by Repetto-Llamazares (2011b).

By comparing the test with long and short submersion times with the simulations of Shafrova (2007) it seems that the freeze-bond area is a key parameter in the estimation of continuum rubble properties. The softening cannot explain the differences between the experiments and the simulations.

Finally there seems to be a fairly good correspondence between the numerical works of Shafrova (2007) and our physical experiments with a similar configurations.

6. AKNOWLEDGEMENTS

The authors gratefully acknowledge the PETROMAKS programme, the Research Council of Norway through the PetroArctic and Petro-Risk programmes, DNV Research and Statoil for funding this study.

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