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Final Report

On

Experimental Determination of Ice Rubble Behaviour and Strength

To

National Research Council of Canada
PERD Ice/Structure Interaction Program

PERD/CHC Report 5 – 115

By

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Department of Civil Engineering
The University of Calgary

February, 2002

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

This report describes the results of a comprehensive test series as part of an on-going programme of research into the behaviour and properties of ice rubble during vertical plane-strain plunge tests. Previous testing of model ice rubble, both in the laboratory and in-situ, has usually involved either vertical plunge tests through the rubble, or horizontal shear box testing; in both cases there is considerable uncertainty regarding the behaviour of the ice rubble, and specifically, the nature of the failure planes. The previous tests (Brown and Azarnejad, 1997, Azarnejad and Brown, 1999, 2001) have provided considerable insight into the behaviour of ice rubble, providing a visual record of failure characteristics, and identifying clear evidence of an effect of speed on the behaviour. Nevertheless, a number of parameters have not yet been fully investigated, and the issue of the differences in behaviour that are observed at different speeds (Azarnejad and Brown, 2001) warrants further investigation.

As a reference test for the strength of ice rubble in model ridges, the plunge test has some attractions. It can be conducted away from the test location of the ridge, disturbs only a small portion of the rubble, and leaves the ice largely in place, an advantage when being used as a measure of rubble strength in ice tanks. The disadvantage of the plunge test is that the nature of the failure planes is unknown, although underwater video has been used on some of the previous tests (McKenna et al, 1996). This video, taken looking up at the underside of the rubble, has provided some information on the nature of the failure plane as it intersects the base of the rubble, but not of the failure planes. A full scale version of the plunge test can be conducted on sea ice ridges, and, indeed, there have now been a number of field test programmes using the plunge test (Lepparanta and Hakala, 1992; Croasdale et al, 1996; Heinonen et al, 2000).

The current test programme focussed on three variables: the platen speed, and the ice block size and the gradation of the size of the ice blocks. The investigation of the speed effects was an outcome of the identification of two different forms of behaviour of the rubble at different platen speeds. At high speeds (> 80 mm/sec) there are no well-defined failure planes, and the ice rubble behaviour in the failure regions is chaotic. At lower speeds (< 30 mm/sec) the failure planes are quite well-defined with very little motion of blocks immediately outside the failure plane. In order to more closely identify the transition between the two forms of behaviour, a number of tests were carried out at intermediate speeds (in the range 30 to 60 mm/sec). An examination of the characteristics of the failure planes had also suggested that the size, and size gradation, of the pieces in the ice rubble may play a role in defining this behaviour.

This report briefly describes the tests carried out in the current phase, the results obtained, and provides further analyses of these results.

Following this introduction, Chapter 2 describes the test program, Chapter 3 the results of the current tests, while Chapter 4 presents analyses of the current and past tests. Finally Chapter 5 presents the conclusions and some recommendations.

Chapter 2 Test Programme

The rational for the experimental design was that the test should closely approximate the in-situ plunge tests as conducted on model rubble formations and in full-scale. The experimental set-up was designed to facilitate observing the characteristics of the resulting failure planes. Because it is more difficult to identify failure planes when they are three-dimensional, the tests were conducted using a rectangular platen which spanned the full width of the test apparatus, thus reducing the test from three-dimensions to two dimensions. The test tank was constructed using Perspex that permitted the observation of the failure planes from the sides of the test apparatus. Otherwise, the tests were conducted in much the same way as the ice tank and in-situ tests, with the platen being forced vertically down through the ice rubble, and the resulting force and displacement being measured.

The test apparatus is shown in Figure 2.1 and consists of a 0.5 m × 0.9 m × 2.45 m Perspex tank and load system supported by a steel frame. The tank dimensions were designed such that there was enough buoyancy force and friction on the non-loaded portion of the rubble to resist the applied loads. Friction at the ends of the tank (Figure 2.1) was increased by gluing small rectangular pieces of Perspex to the walls of the tank. The centre section of the tank was kept clear to avoid interfering with the failure mode of the rubble, and to permit viewing and recording the failure mode.

Load was applied through a rectangular platen attached to one end of a hydraulic ram, and monitored using a 2 kN load cell. The hydraulic ram had a maximum stroke and rate of 0.75 m and 0.12 m/s respectively. The platen was 0.25 m by 0.5 m, machined from 0.019 m (3/4″) thick aluminum plate. The long side of the platen covers almost the entire width of the tank, leaving only a small gap of several millimeters at the two ends to avoid contact, and the resulting friction between the platen and the walls. The friction forces would contaminate the load recorded by the load cell. Displacement of the platen was measured using a linear potentiometer with a maximum stroke of 0.355 m.

Ice was obtained from three sources: standard ice making machines, a specially purchased machine that produces larger ice pieces, and ice purchased commercially. All of the ice used was fresh water ice and was stored in a freezer, prior to use. The ice obtained from the standard ice making machines was 5 mm by 8 mm by 20 mm. The larger ice pieces provided by the specially purchased machine were 35 x 35 x 15 mm, but tended to be somewhat hollowed. The ice obtained commercially was graded with a maximum piece size of >56 mm.

The tank was filled with fresh water, and then the required amount of ice was placed to the desired depth, and levelled to ensure a uniform depth. When placed in the tank, the ice rubble can be described as a loose agglomeration of small blocks, lacking cohesion. A thermocouple measures the room temperature. All of the tests were documented using a digital video camera, looking through one side of the tank.

Tests that are described as "zero ageing" were conducted as soon as possible after the ice had been placed in the tank. The premise was that there has not been sufficient time for significant cohesive bonds to form prior to the loading of the rubble. However, as illustrated in the chapter 3, the conditions in the tank, and when the ice was placed, clearly play a significant role in determining the consolidated conditions of the ice rubble. For tests for which consolidation was planned, any fully consolidated layer that had previously formed at the surface was broken and the ice rubble was stirred to break the bonds between the ice pieces and provide a uniform thickness of rubble. The room was subsequently kept at a constant temperature at –2°C for the required number of hours of ageing. It was observed in previous test programmes that, for consolidation periods greater than one hour, the consolidated layer developed significant strength and the ultimate load included the flexural failure of this layer. Therefore for any curing periods (one hour or more), the consolidated layer was cut with a saw along the long (0.5 m) sides of the platen across the width of the tank, before applying the load. The saw cuts were made within 5 mm of the edge of the platen, so as to ensure that there was no interaction between the isolated portion and the rest of the consolidated layer. Any bond between the rubble and the sides of the tank was also broken at this time.

Once the rubble has been prepared for the test, the test was conducted by forcing the platen down through the ice at a controlled rate. Experience has allowed a selection of platen speeds at various intervals between 12 mm/sec and 115 mm/sec. For this test series, platen speeds of 12mm/sec, 25 mm/sec. 30 mm/sec, 45mm/sec and 115 mm/sec, were used. The load and displacement were recorded at a frequency 30Hz. The data is recorded on a laboratory computer, and subsequently input into an Excel spreadsheet for analysis.

Figure 2.2 illustrates a typical load and displacement plot from one test. In order to obtain the maximum deflection corresponding to the peak load, the time corresponding to zero deflection is selected by examining the plots from the data. The recorded displacement at this time was then subtracted from the recorded displacement at the time of maximum load to obtain the displacement at peak load.

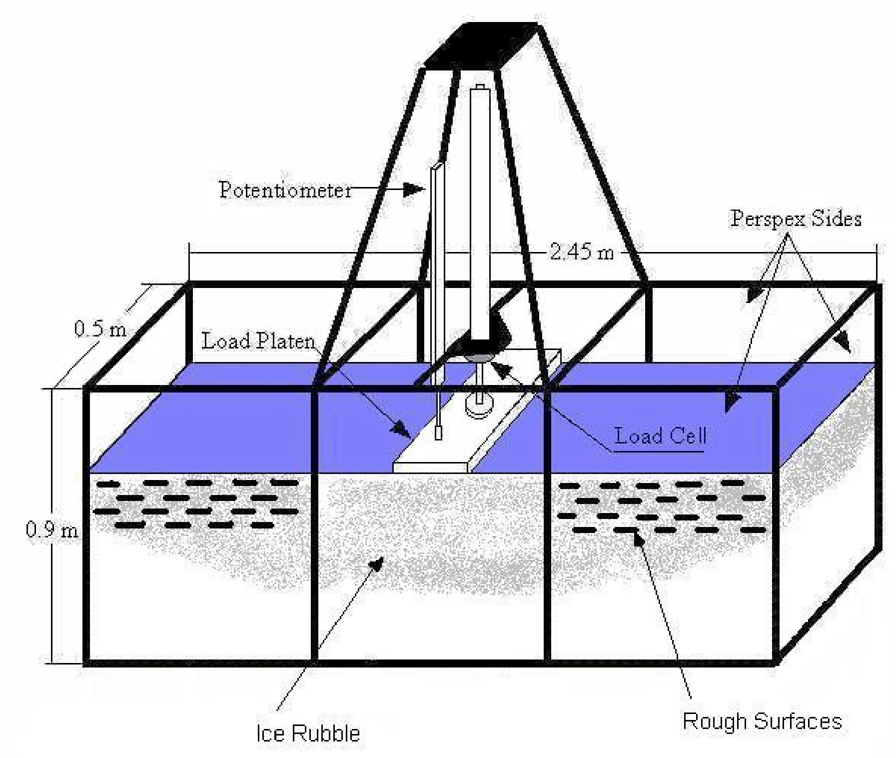
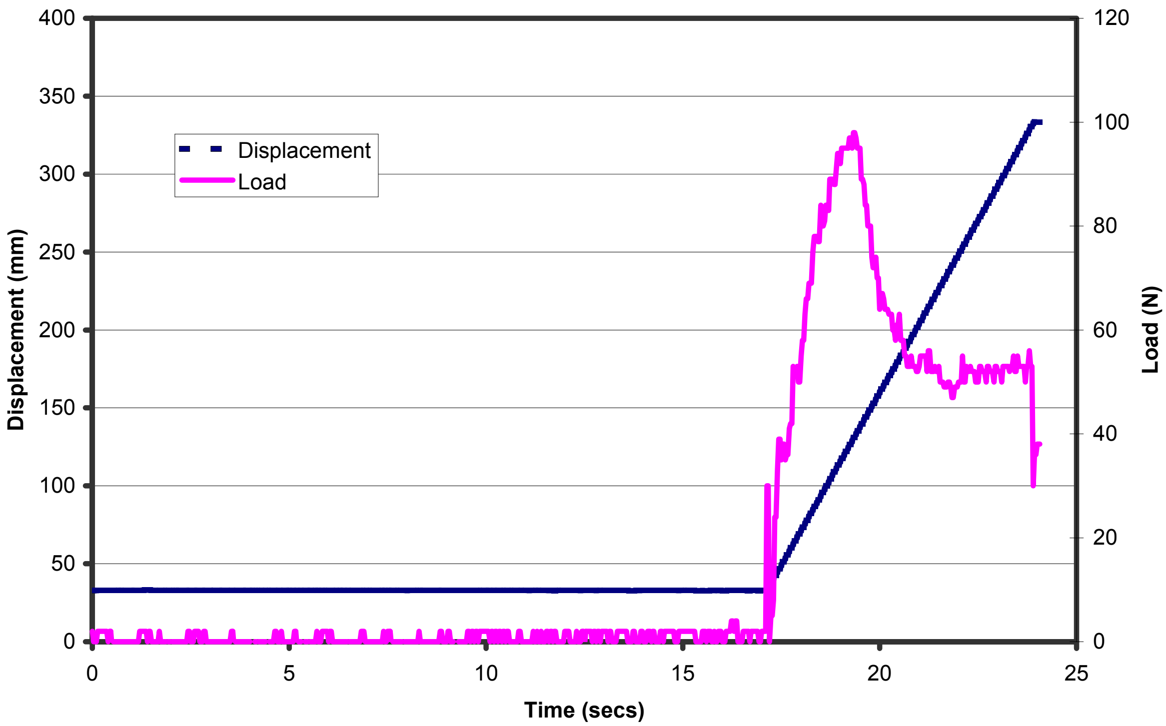


Figure 2.1 Test Arrangement

Figure 2.2 Typical Result Plot



Chapter 3 Test Programme Results

The current test programme focussed on an investigation of: the effect of block size, further assessment of the effect of speed, and the identification of the threshold speed associated with the change in behaviour (Azernejad and Brown, 2001). In total, 112 tests were conducted using the three different block configurations. The tests are listed in Table 3.1 with the relevant parameters. As indicated previously, the larger block size was hollow, and therefore the resulting rubble was of higher porosity than the rubble from the smaller blocks. Table 3.2 summarises the basic properties of the rubble resulting from the three different sources of ice blocks.

The commercial ice came in a variety of piece sizes, with a maximum size that was greater than 56 mm. A sample of the ice was sieved in the cold room and the results of this analysis are presented in Figure 3.1. Although the gradation of piece sizes permitted more close packing of the ice pieces, the overall porosity (0.386) was still greater than the historically expected values in the 0.2 to 0.3 range.

The results of the current series of test are presented in Table 3.3. The "b_ice" tests represent the basic set of tests using the larger ice blocks. Tests were conducted for three different rubble ice thicknesses, three platen speeds, and three periods of consolidation. The results of these tests are shown in Figures 3.2 to 3.4 as plots of effective shear strength against velocity, for the 20 cm, 30 cm, and 40 cm deep rubble respectively. While the 20 cm deep rubble results clearly suggest some effect of consolidation on strength, this becomes less apparent with the deeper rubble. This, however, is not altogether surprising, given that the periods of consolidation for the three different rubble depths are identical.

The tests identified as "speed", were carried out in an attempt to further identify the transition between behaviour that is clearly that of soils, and can be described as Mohr-Coulomb, and the behaviour at higher platen speeds that does not appear to fit this form of behaviour.

Accordingly, a set of tests for two periods of consolidation was carried out at two intermediate velocities: 30 mm/sec and 45 mm/sec. All tests were carried out with the larger rubble pieces, and at a rubble depth of 40 cm. The results of the complete set of tests for the larger ice pieces, at a rubble depth of 40 cm, are presented in Figure 3.5, for zero, and one hour, consolidation.

The results presented in Table 3.3, for tests identified as “test” and “arc”, were carried out using the commercial ice. All tests were carried out at zero hours consolidation and with a rubble depth of 40 cm. For the second test series, identified as “arc”, the ice had not previously been stored in a freezer. The ice was therefore significantly warmer than the ice in the corresponding tests identified as “test” when placed in the tank. As is shown in Chapter 4, the differences in the two sets of results were quite significant.

Table 3.1 Test Summary

Name	Ice Type	Thickness (cm)	Speed (mm/sec)	Age (hours)
B_ice3	Large block	20	13.1	0
B_ice4	Large block	20	12.6	0
B_ice5	Large block	20	12.8	0
B_ice6	Large block	20	71.9	0
B_ice12	Large block	20	73.5	0
B_ice13	Large block	20	72.0	0
B_ice15	Large block	20	109.9	0
B_ice17	Large block	20	109.5	0
B_ice19	Large block	20	108.6	0
B_ice20	Large block	20	13.6	1
B_ice21	Large block	20	12.3	1
B_ice22	Large block	20	11.8	1
B_ice23	Large block	20	68.4	1
B_ice24	Large block	20	69.9	1
B_ice26	Large block	20	70.8	1
B_ice27	Large block	20	109.1	1
B_ice28	Large block	20	109.1	1
B_ice29	Large block	20	108.9	1
B_ice30	Large block	20	11.3	2
B_ice31	Large block	20	11.4	2
B_ice32	Large block	20	70.8	2
B_ice33	Large block	20	70.7	2
B_ice34	Large block	20	107.9	2
B_ice35	Large block	20	108.8	2
B_ice36	Large block	30	11.5	0
B_ice37	Large block	30	10.7	0
B_ice38	Large block	30	10.5	0

Name	Ice Type	Thickness (cm)	Speed (mm/sec)	Age (hours)
B_ice39	Large block	30	71.1	0
B_ice40	Large block	30	71.0	0
B_ice42	Large block	30	70.8	0
B_ice43	Large block	30	111.4	0
B_ice44	Large block	30	110.4	0
B_ice45	Large block	30	109.7	0
B_ice46	Large block	30	12.5	1
B_ice47	Large block	30	12.6	1
B_ice48	Large block	30	12.2	1
B_ice51	Large block	30	70.0	1
B_ice54	Large block	30	71.9	1
B_ice55	Large block	30	71.8	1
B_ice56	Large block	30	110.1	1
B_ice57	Large block	30	110.2	1
B_ice58	Large block	30	110.0	1
B_ice59	Large block	30	9.5	2
B_ice60	Large block	30	9.4	2
B_ice61	Large block	30	67.9	2
B_ice62	Large block	30	67.9	2
B_ice63	Large block	30	108.4	2
B_ice66	Large block	30	109.7	2
B_ice67	Large block	40	9.0	0
B_ice68	Large block	40	9.1	0
B_ice69	Large block	40	8.9	0
B_ice72	Large block	40	66.8	0
B_ice73	Large block	40	67.7	0
B_ice75	Large block	40	69.3	0
B_ice77	Large block	40	108.6	0

Name	Ice Type	Thickness (cm)	Speed (mm/sec)	Age (hours)
B_ice79	Large block	40	111.1	0
B_ice81	Large block	40	111.0	0
B_ice82	Large block	40	10.2	1
B_ice83	Large block	40	10.3	1
B_ice85	Large block	40	10.7	1
B_ice86	Large block	40	76.3	1
B_ice88	Large block	40	76.4	1
B_ice89	Large block	40	75.6	1
B_ice90	Large block	40	109.1	1
B_ice91	Large block	40	109.2	1
B_ice93	Large block	40	108.0	1
Speed14	Large block	40	31.3	0
Speed15	Large block	40	28.5	0
Speed17	Large block	40	28.8	0
Speed18	Large block	40	47.9	0
Speed19	Large block	40	47.5	0
Speed20	Large block	40	46.5	0
Speed22	Large block	40	28.2	1
Speed25	Large block	40	28.2	1
Speed26	Large block	40	27.1	1
Speed27	Large block	40	44.8	1
Speed34	Large block	40	45.0	1
Speed36	Large block	40	45.0	1
Test6	Commercial	40	10.9	0
Test8	Commercial	40	10.9	0
Test9	Commercial	40	11.6	0
Test10	Commercial	40	28.8	0
Test11	Commercial	40	25	0

Name	Ice Type	Thickness (cm)	Speed (mm/sec)	Age (hours)
Test12	Commercial	40	28.7	0
Test13	Commercial	40	48.0	0
Test14	Commercial	40	48.0	0
Test15	Commercial	40	48.0	0
Test16	Commercial	40	72.1	0
Test17	Commercial	40	77.2	0
Arc1	Commercial	40	11.1	0
Arc3	Commercial	40	11.3	0
Arc4	Commercial	40	11.7	0
Arc5	Commercial	40	24.1	0
Arc6	Commercial	40	24.4	0
Arc7	Commercial	40	24.4	0
Arc8	Commercial	40	35.6	0
Arc9	Commercial	40	35.7	0
Arc10	Commercial	40	35.2	0
Arc11	Commercial	40	49.2	0
Arc12	Commercial	40	49.6	0
Arc13	Commercial	40	48.7	0
Arc14	Commercial	40	80.8	0
Arc15	Commercial	40	79.6	0
Arc16	Commercial	40	79.9	0
Arc17	Commercial	40	104.6	0
Arc18	Commercial	40	104.3	0
Arc19	Commercial	40	12.6	0
Arc20	Commercial	40	25.9	0
Arc21	Commercial	40	38.1	0
Arc22	Commercial	40	24.2	0
Arc23	Commercial	40	24.1	0

Table 3.2 Rubble Properties

Rubble Type	Density	Porosity
Small block	0.895	0.5
Large Block	0.939	0.648
Commercial	0.924	0.386

Table 3.3 Results

File Name	Velocity (mm/s)	Height (m)	Age (hrs)	Peak (N)	Residual (N)	Inertia (N)	Shear Strength (Pa)	Net Force (N)	phi(deg)
b_ice3	13.09	0.2	0	47.8	42	2.158	18.581	3.642	24.30
b_ice4	12.58	0.2	0	60	46.2	2.061	59.893	11.739	55.52
b_ice5	12.85	0.2	0	47.2	42.2	2.112	14.736	2.888	19.70
b_ice6	71.94	0.2	0	78.6	48	13.340	88.061	17.260	64.97
b_ice12	73.51	0.2	0	72.2	39.8	13.638	95.725	18.762	66.76
b_ice13	72.04	0.2	0	78	42	13.358	115.519	22.642	70.42
b_ice15	109.9	0.2	0	76	32.4	20.554	117.581	23.046	70.73
b_ice17	109.5	0.2	0	87.6	38.2	20.472	147.590	28.928	74.45
b_ice19	108.6	0.2	0	82	40	20.302	110.702	21.698	69.63
b_ice20	13.57	0.2	1	51.6	41.6	2.250	39.541	7.750	43.86
b_ice21	12.30	0.2	1	62.4	47.6	2.009	65.262	12.791	57.78
b_ice22	11.79	0.2	1	50.8	38.4	1.911	53.513	10.489	52.45
b_ice23	68.45	0.2	1	79	46	12.676	103.692	20.324	68.38
b_ice24	69.89	0.2	1	72.8	36.2	12.949	120.667	23.651	71.19
b_ice26	70.78	0.2	1	80.6	43.6	13.119	121.840	23.881	71.36
b_ice27	109.1	0.2	1	93.8	37.4	20.393	183.710	36.007	77.40
b_ice28	109.1	0.2	1	98.8	41.2	20.405	189.771	37.195	77.80
b_ice29	108.9	0.2	1	95.6	44.2	20.365	158.342	31.035	75.46
b_ice30	11.31	0.2	2	50.2	40	1.819	42.759	8.381	46.10
b_ice31	11.44	0.2	2	56	42.2	1.844	61.002	11.956	56.01
b_ice32	70.84	0.2	2	70	33	13.131	121.779	23.869	71.35
b_ice33	70.67	0.2	2	76	34.8	13.098	143.376	28.102	74.01
b_ice34	107.9	0.2	2	96.6	34.8	20.181	212.342	41.619	79.06
b_ice35	108.8	0.2	2	98.4	33.8	20.351	225.759	44.249	79.70
b_ice36	11.55	0.3	0	63.2	47.8	1.865	46.036	13.535	36.72
b_ice37	10.66	0.3	0	65.2	45.8	1.696	60.216	17.704	44.29
b_ice38	10.49	0.3	0	61.2	45	1.664	49.442	14.536	38.69
b_ice39	71.13	0.3	0	100	53.4	13.185	113.657	33.415	61.51
b_ice40	71.00	0.3	0	102	53.4	13.160	120.543	35.440	62.90
b_ice42	70.76	0.3	0	92.6	51.8	13.115	94.167	27.685	56.77
b_ice43	111.4	0.3	0	119.2	48.2	20.829	170.648	50.171	70.14
b_ice44	110.4	0.3	0	118	47.6	20.650	169.218	49.750	69.98
b_ice45	109.7	0.3	0	117.2	53.4	20.521	147.207	43.279	67.27
b_ice46	12.54	0.3	1	64.2	45.4	2.054	56.959	16.746	42.70
b_ice47	12.57	0.3	1	56.6	41.6	2.059	44.015	12.941	35.49
b_ice48	12.24	0.3	1	60.2	41.2	1.996	57.836	17.004	43.14
b_ice51	69.97	0.3	1	85.4	38.2	12.966	116.442	34.234	62.09
b_ice54	71.89	0.3	1	98.6	50.4	13.330	118.605	34.870	62.52
b_ice55	71.76	0.3	1	100.4	45	13.305	143.179	42.095	66.70

File Name	Velocity (mm/s)	Height (m)	Age (hrs)	Peak (N)	Residual (N)	Inertia (N)	Shear Strength (Pa)	Net Force (N)	phi(deg)
b_ice56	110.1	0.3	1	108.2	43.8	20.598	148.988	43.802	67.52
b_ice57	110.2	0.3	1	123.4	42.8	20.615	204.029	59.985	73.19
b_ice58	110.0	0.3	1	116.4	44.2	20.577	175.590	51.623	70.65
b_ice59	9.52	0.3	2	70.4	50.6	1.481	62.310	18.319	45.27
b_ice60	9.35	0.3	2	73.8	57	1.448	52.217	15.352	40.23
b_ice61	67.95	0.3	2	92.8	31.8	12.582	164.689	48.419	69.48
b_ice62	67.87	0.3	2	106.4	44.6	12.566	167.462	49.234	69.79
b_ice63	108.4	0.3	2	115.2	40.2	20.276	186.135	54.724	71.68
b_ice66	109.7	0.3	2	99.2	42	20.521	124.758	36.679	63.69
b_ice67	8.97	0.4	0	83	62.2	1.376	49.550	19.424	31.05
b_ice68	9.11	0.4	0	98.4	81	1.402	40.812	15.998	26.37
b_ice69	8.89	0.4	0	94.2	76.8	1.360	40.920	16.040	26.43
b_ice72	66.79	0.4	0	111.4	51.8	12.362	120.505	47.238	55.68
b_ice73	67.71	0.4	0	114.4	54.8	12.536	120.061	47.064	55.58
b_ice75	69.31	0.4	0	115.8	62.8	12.839	102.451	40.161	51.23
b_ice77	108.55	0.4	0	163	65	20.296	198.223	77.704	67.47
b_ice79	111.1	0.4	0	165.4	58	20.783	220.963	86.617	69.59
b_ice81	111.0	0.4	0	158.6	63.2	20.758	190.413	74.642	66.64
b_ice82	10.17	0.4	1	86.2	65.6	1.604	48.460	18.996	30.49
b_ice83	10.29	0.4	1	80.6	68	1.626	27.994	10.974	18.78
b_ice85	10.70	0.4	1	92.8	65	1.703	66.573	26.097	38.97
b_ice86	76.25	0.4	1	119.2	60.2	14.159	114.392	44.842	54.27
b_ice88	76.35	0.4	1	124.8	62.2	14.178	123.525	48.422	56.34
b_ice89	75.60	0.4	1	139	58.6	14.035	169.298	66.365	64.09
b_ice90	109.1	0.4	1	140.8	54.6	20.405	167.845	65.795	63.90
b_ice91	109.2	0.4	1	140.6	50	20.418	179.037	70.182	65.33
b_ice93	108.0	0.4	1	140.4	53.6	20.198	169.904	66.602	64.17
speed14	31.3	0.4	0	39	12.3	5.618	53.781	21.082	33.16
speed15	28.5	0.4	0	101	67	5.086	73.760	28.914	41.87
speed17	28.8	0.4	0	87	52	5.143	76.166	29.857	42.78
speed22	28.2	0.4	1	87	54	5.029	71.355	27.971	40.93
speed25	28.2	0.4	1	97	58	5.029	86.661	33.971	46.48
speed26	27.1	0.4	1	86	53	4.820	71.888	28.180	41.14
speed18	47.9	0.4	0	111	61	8.772	105.173	41.228	51.96
speed19	47.5	0.4	0	36	17	8.696	26.286	10.304	17.71
speed20	46.5	0.4	0	94	53	8.506	82.893	32.494	45.21
speed27	44.8	0.4	1	98	49	8.183	104.125	40.817	51.68
speed34	45	0.4	1	98	55	8.221	88.722	34.779	47.15
speed36	45	0.4	1	111	52	8.221	129.538	50.779	57.58
test6	10.9	0.4	0	131	101	1.742	72.087	28.258	22.10
test8	10.9	0.4	0	109	76	1.742	79.740	31.258	24.19

File Name	Velocity (mm/s)	Height (m)	Age (hrs)	Peak (N)	Residual (N)	Inertia (N)	Shear Strength (Pa)	Net Force (N)	phi(deg)
test9	11.6	0.4	0	115	75	1.875	97.258	38.125	28.72
test10	28.8	0.4	0	112	72	5.143	88.921	34.857	26.61
test11	25	0.4	0	148	98	4.421	116.273	45.579	33.23
test12	28.7	0.4	0	137	80	5.124	132.337	51.876	36.71
test13	48	0.4	0	107	59	8.791	100.023	39.209	29.40
test14	48	0.4	0	151	86	8.791	143.390	56.209	38.94
test15	48	0.4	0	140	71	8.791	153.594	60.209	40.88
test16	72.1	0.4	0	166	81	13.370	182.730	71.630	45.84
test17	77.2	0.4	0	148	78	14.339	141.992	55.661	38.66
arc1	11.1	0.4	0	106	79	1.780	64.337	25.220	19.92
arc3	11.3	0.4	0	109	77	1.818	76.995	30.182	23.45
arc4	11.7	0.4	0	103	72	1.894	74.250	29.106	22.70
arc5	24.1	0.4	0	109	69	4.250	91.199	35.750	27.20
arc6	24.4	0.4	0	99	62	4.307	83.401	32.693	25.17
arc7	24.4	0.4	0	106	65	4.307	93.605	36.693	27.81
arc8	35.6	0.4	0	95	63	6.435	65.217	25.565	20.17
arc9	35.7	0.4	0	101	59	6.454	90.679	35.546	27.06
arc10	35.2	0.4	0	103	62	6.359	88.370	34.641	26.47
arc11	49.2	0.4	0	115	66	9.019	101.992	39.981	29.88
arc12	49.6	0.4	0	100	61	9.095	76.288	29.905	23.26
arc13	48.7	0.4	0	109	61	8.924	99.684	39.076	29.32
arc14	80.8	0.4	0	123	66	15.023	107.084	41.977	31.10
arc15	79.6	0.4	0	130	66	14.795	125.523	49.205	35.27
arc16	79.9	0.4	0	119	63	14.852	104.969	41.148	30.60
arc17	104.6	0.4	0	145	64	19.545	156.773	61.455	41.46
arc18	104.3	0.4	0	143	61	19.488	159.469	62.512	41.94
arc19	12.6	0.4	0	114	77	2.065	89.120	34.935	26.66
arc20	25.9	0.4	0	91	60	4.592	67.367	26.408	20.78
arc21	38.1	0.4	0	112	73	6.910	81.862	32.090	24.76
arc22	24.2	0.4	0	95	56	4.269	88.599	34.731	26.53
arc23	24.1	0.4	0	98	56	4.250	96.301	37.750	28.48

Figure 3.1 Sieve Analysis of Commercial Ice

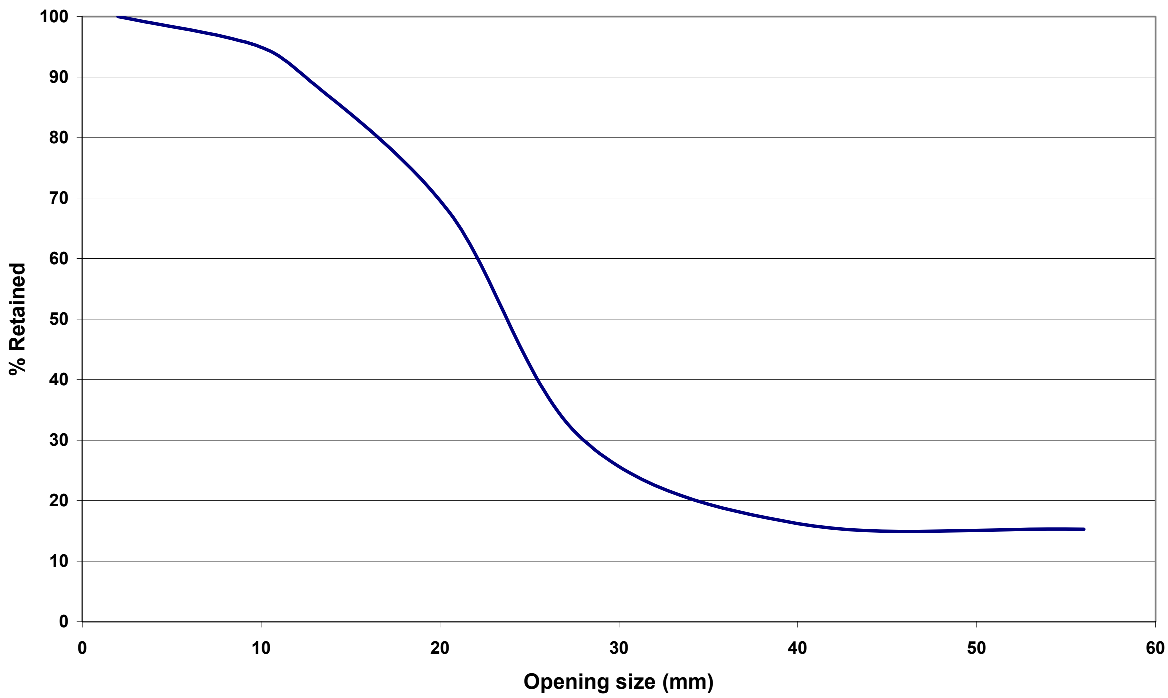


Figure 3.2 Shear Strength vs. Speed
Rubble Thickness - 0.2 m

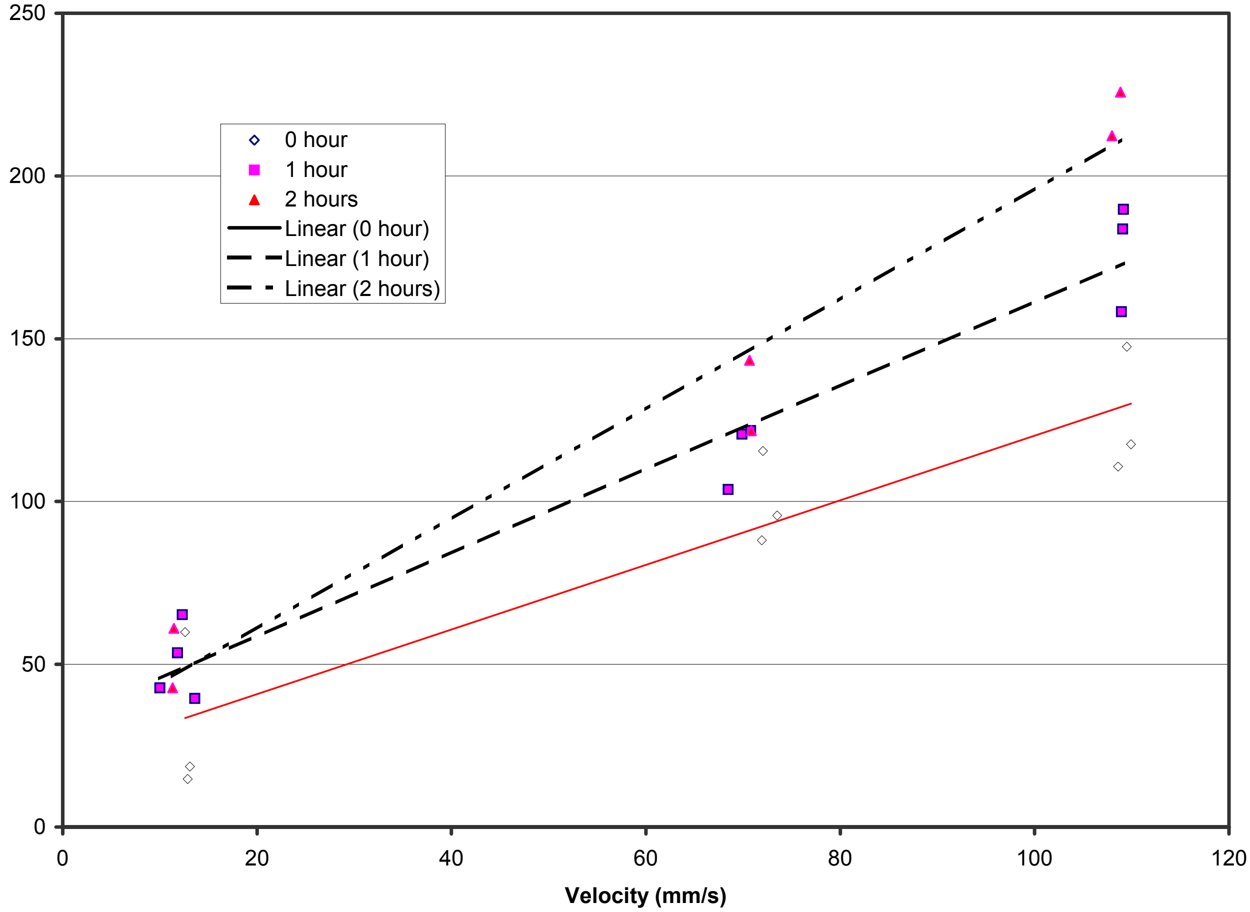
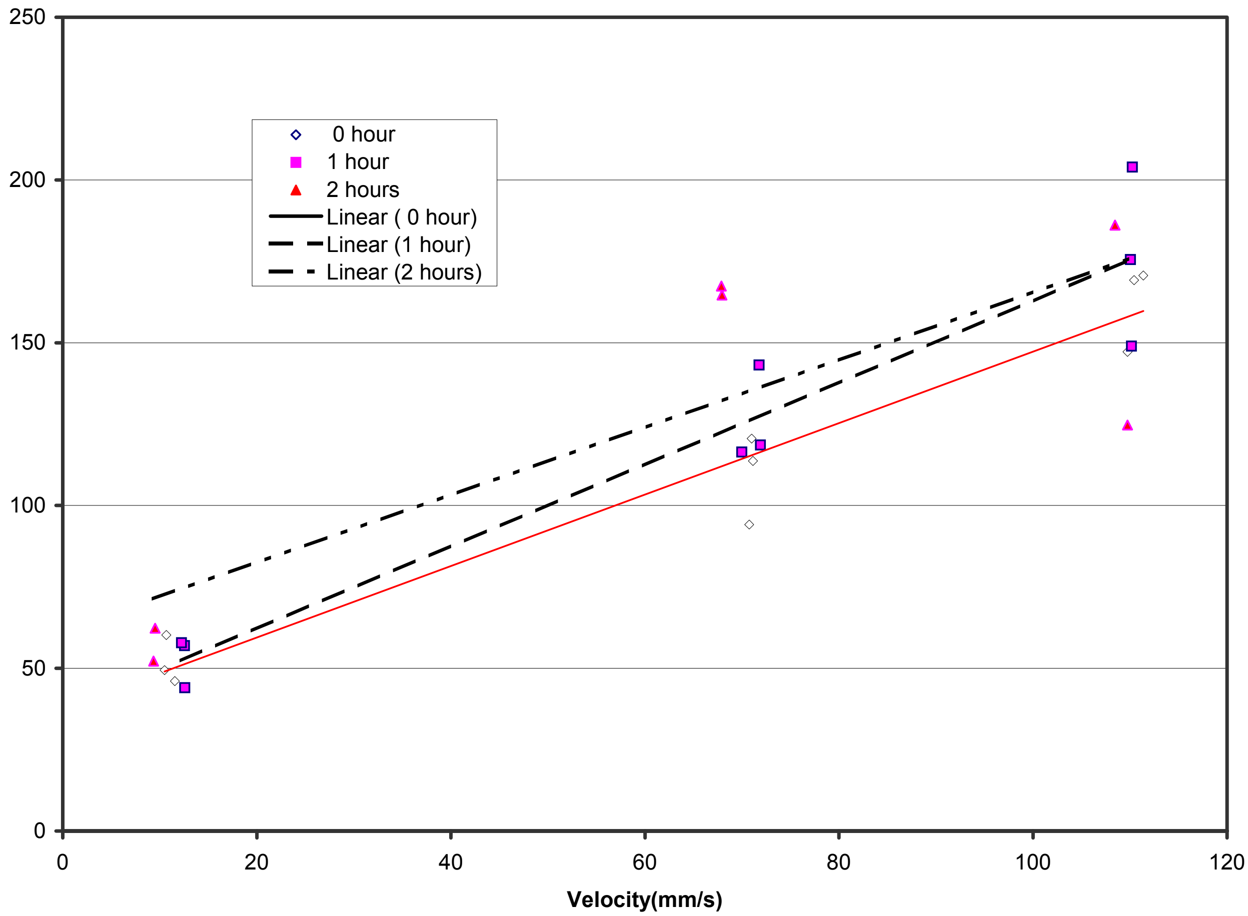


Figure 3.3 Shear Strength vs. Speed
Rubble Thickness - 0.3 m



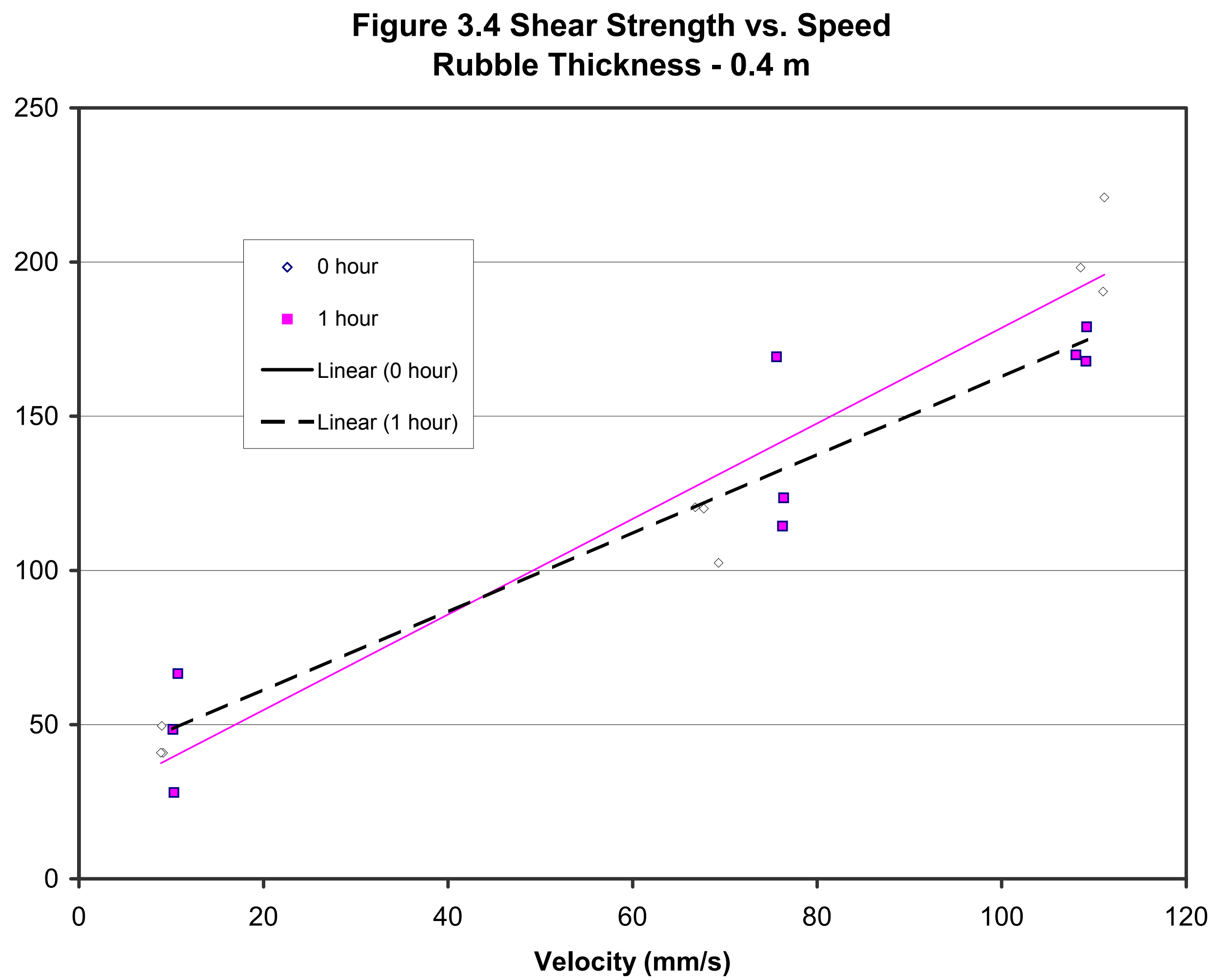
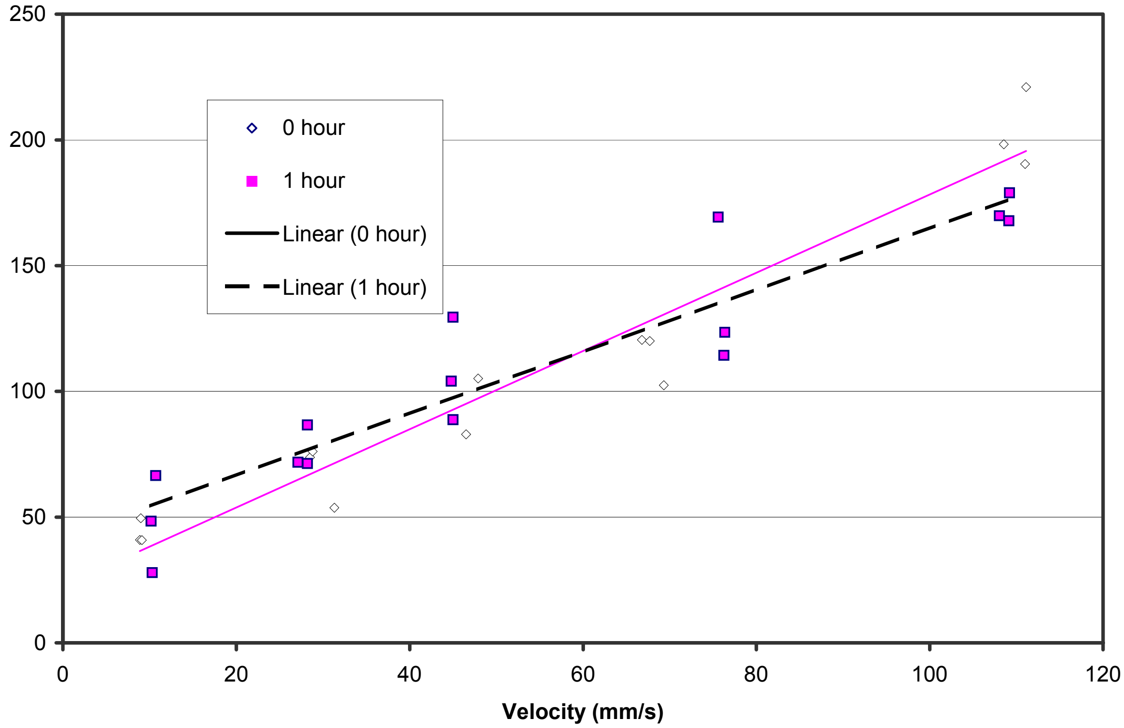


Figure 3.4 Shear Strength vs. Speed
Rubble Thickness - 0.4 m
250
200
150
100
50
0
0
20
40
60
80
100
120
Velocity (mm/s)
0 hour
1 hour
Linear (0 hour)
Linear (1 hour)

Figure 3.5 Extended Shear Strength vs. Speed
Rubble Thickness - 0.4 m



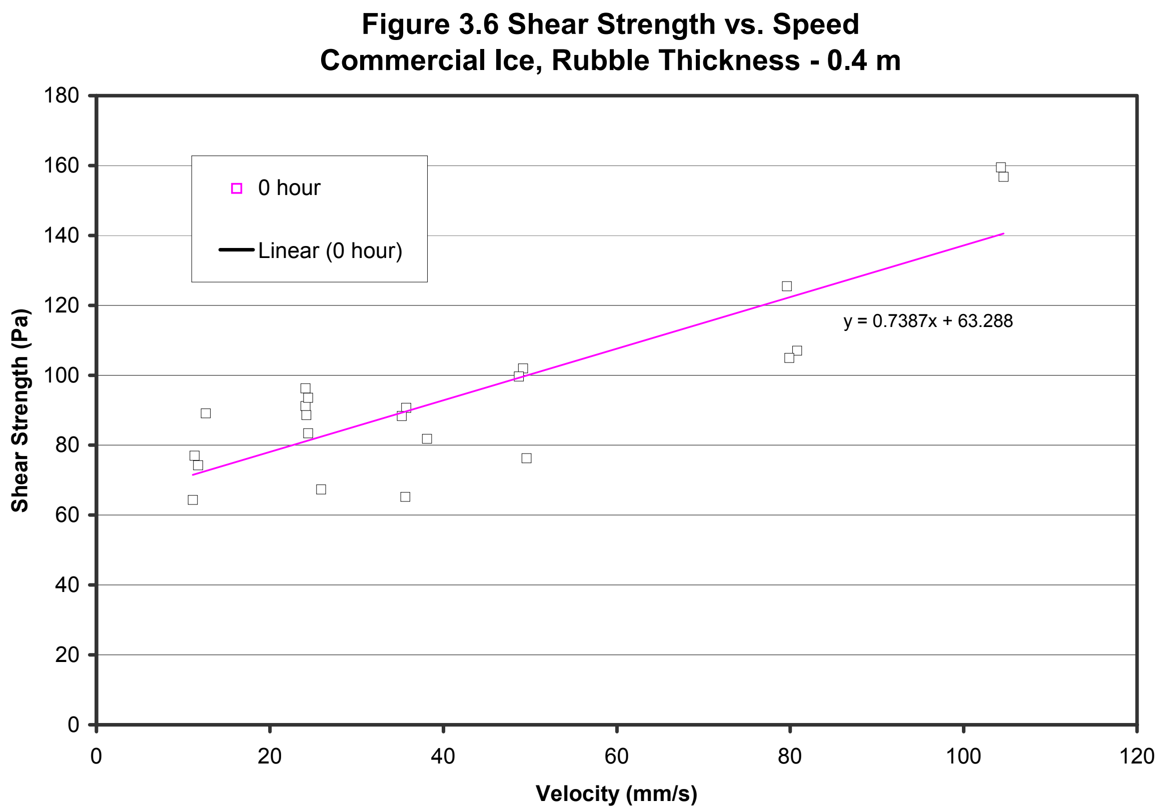


Figure 3.6 Shear Strength vs. Speed
Commercial Ice, Rubble Thickness - 0.4 m
0 hour
Linear (0 hour)
y = 0.7387x + 63.288
Shear Strength (Pa)
Velocity (mm/s)
0
20
40
60
80
100
120
140
160
180
0
20
40
60
80
100
120

Chapter 4 Analysis of Results

The primary foci of the current series of experiments and their analysis, has been the effect of piece size on the shear strength, and derived properties of the rubble, and later, closer investigation of the effect of speed on the behaviour of the ice rubble.

To assess the effect of piece size, Figures 4.1 to 4.6 provide comparisons between the results for the two uniform piece sizes used: the smaller sizes used in previous work, and the larger piece size used in the current work and reported in Chapter 3. Figure 4.1 and 4.2 compare the results for 20 cm deep rubble, for zero hour and one hour consolidation times respectively. Figures 4.3 and 4.4 provide the corresponding results for 30 cm deep rubble, Figure 4.5 and 4.6 for 40 cm deep rubble.

While there is little difference in the results when there has been no consolidation, the results after one hour consolidation do show some difference, with the behaviour of the smaller blocks being characterised by a higher effective shear strength. This is consistent at all rubble depths. There may be several reasons for this difference in behaviour, including the greater porosity of the larger blocks, and the potential that the greater number of contacts between blocks that occurs with the smaller blocks, both of which would result in a higher effective shear strength. Figure 4.7 presents the results of Figure 4.5 with the results from the graded commercial ice added. From this Figure, it is apparent that the strength of the graded ice is greater at the low platen speeds, but is significantly less at the higher speeds. This difference in relative strength may be consistent with the differences in behaviour observed in the other tests, where the graded ice would result in higher strength if the behaviour was typical of granular materials at the slow speeds. At the higher speeds, where hydrodynamic effects are more prevalent, the variation in piece size may be result in the lower effective strength.

Figure 4.8 presents the results of Figure 4.7 as an effective friction angle, φ. However, the results presented in Figure 4.8 show no difference from the results of effective shear strength, despite the differences in porosity. Figure 4.9 also presents the results for friction angle, but presents the results for both sets of tests using the commercial, graded, ice. Here, the differences in the results for the two sets of tests are quite apparent. Not surprising, the tests carried out with the warmer ice, not previously stored in the freezer, result in lower effective friction angle than the results for the tests carried out with the colder ice.

Finally, Figure 4.10 plots the results for the friction angle for the three different ice types used to date, but with the lower speed tests separated from the higher speed tests. The linear regression lines clearly suggest that there is a difference in the friction angle/speed relation within the two speed ranges. At the lower speeds, the behaviour, based on the video record, exhibits well defined failure planes, in keeping with classical soil behaviour. At the higher speeds, however, the failure planes are less defined. Generally they exhibit a band within which, individual particles are subject to rigid body motions. It is proposed that hydrodynamic effects are influencing the rubble behaviour at these higher speeds.

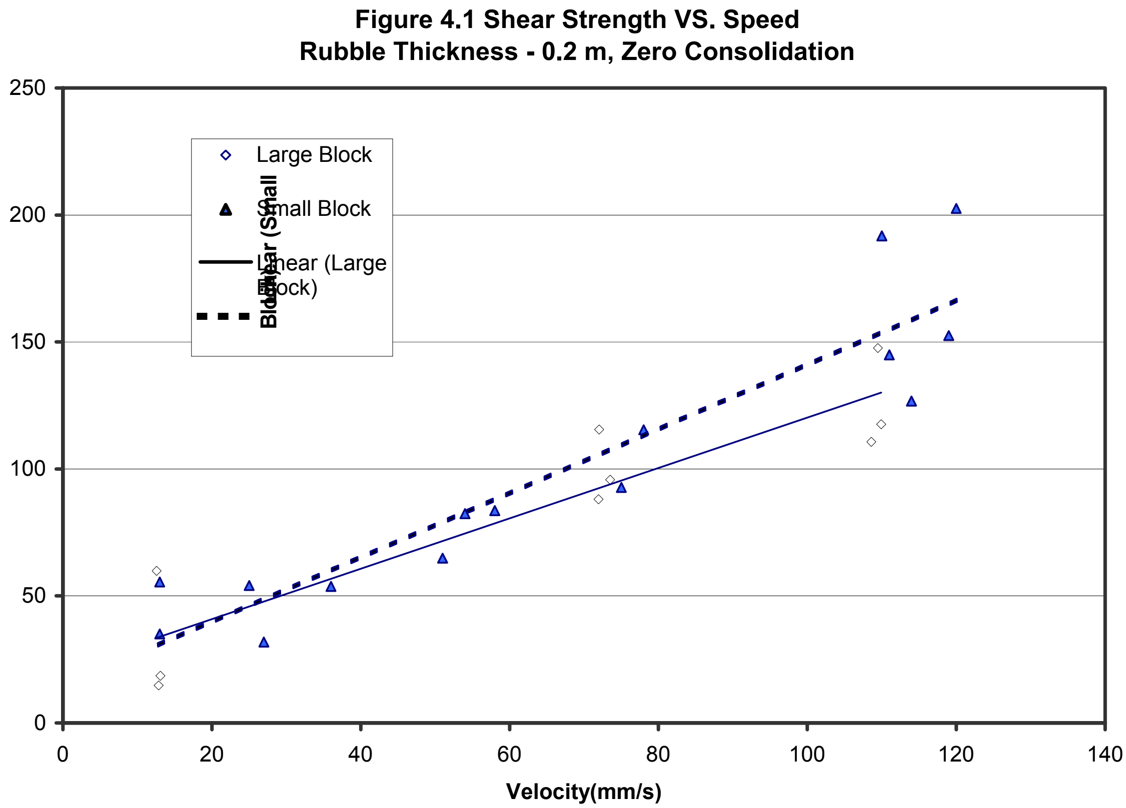
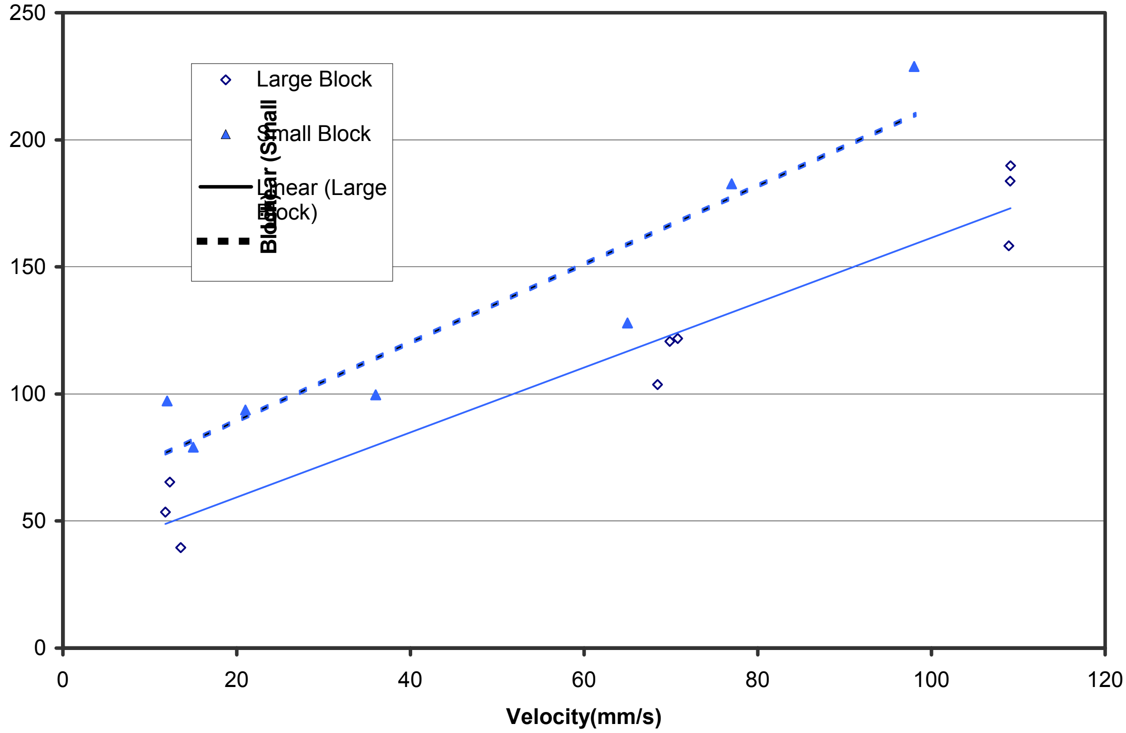


Figure 4.1 Shear Strength VS. Speed
Rubble Thickness - 0.2 m, Zero Consolidation
250
200
150
100
50
0
0
20
40
60
80
100
120
140
Velocity(mm/s)
Large Block
Small Block
Linear (Large Block)
Linear (Small Block)

Figure 4.2 Shear Strength VS. Speed
Rubble Thickness - 0.2 m, One Hour Consolidation



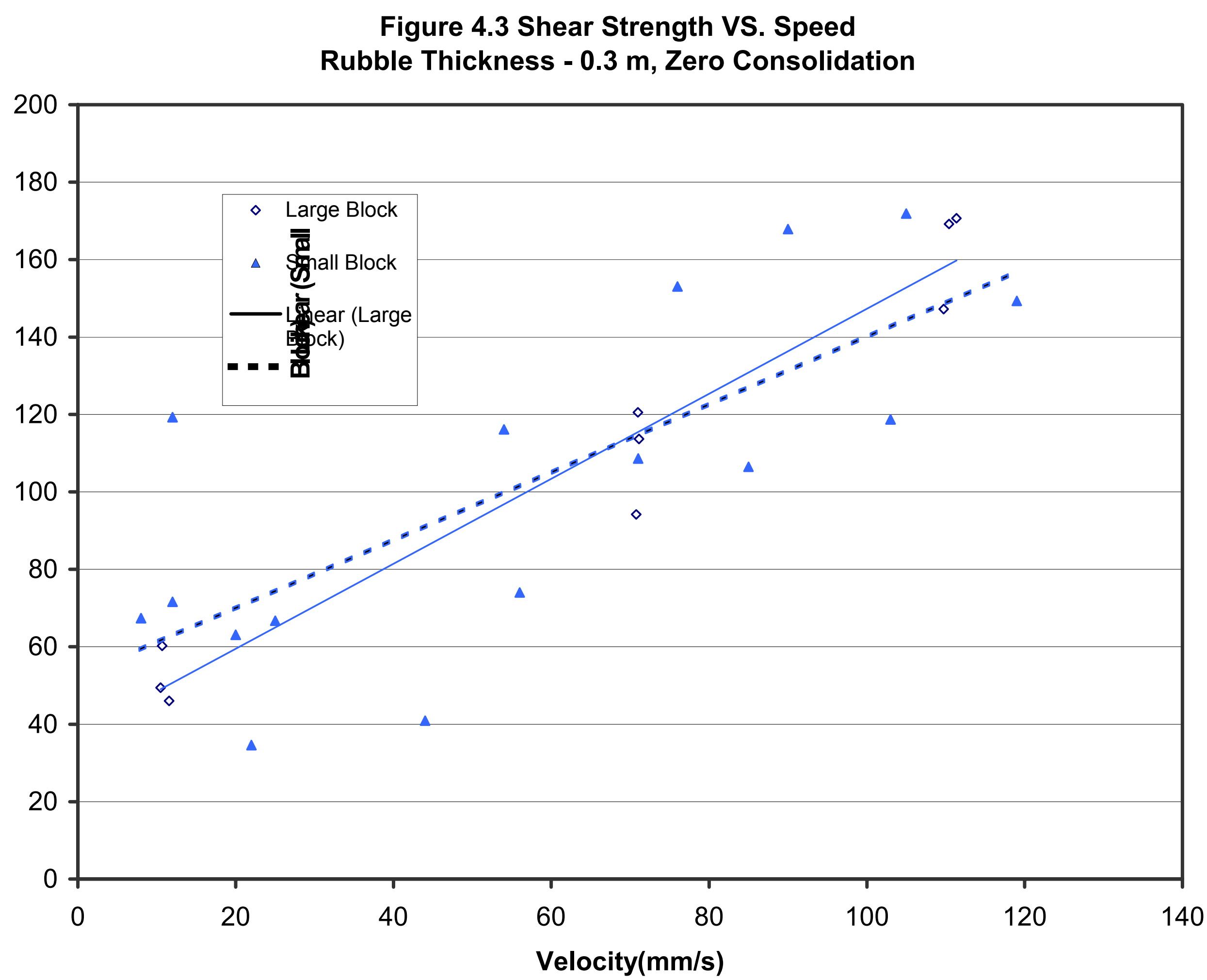


Figure 4.3 Shear Strength VS. Speed
Rubble Thickness - 0.3 m, Zero Consolidation
200
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Velocity(mm/s)
Large Block
Small Block
Linear (Large Block)
Linear (Small Block)

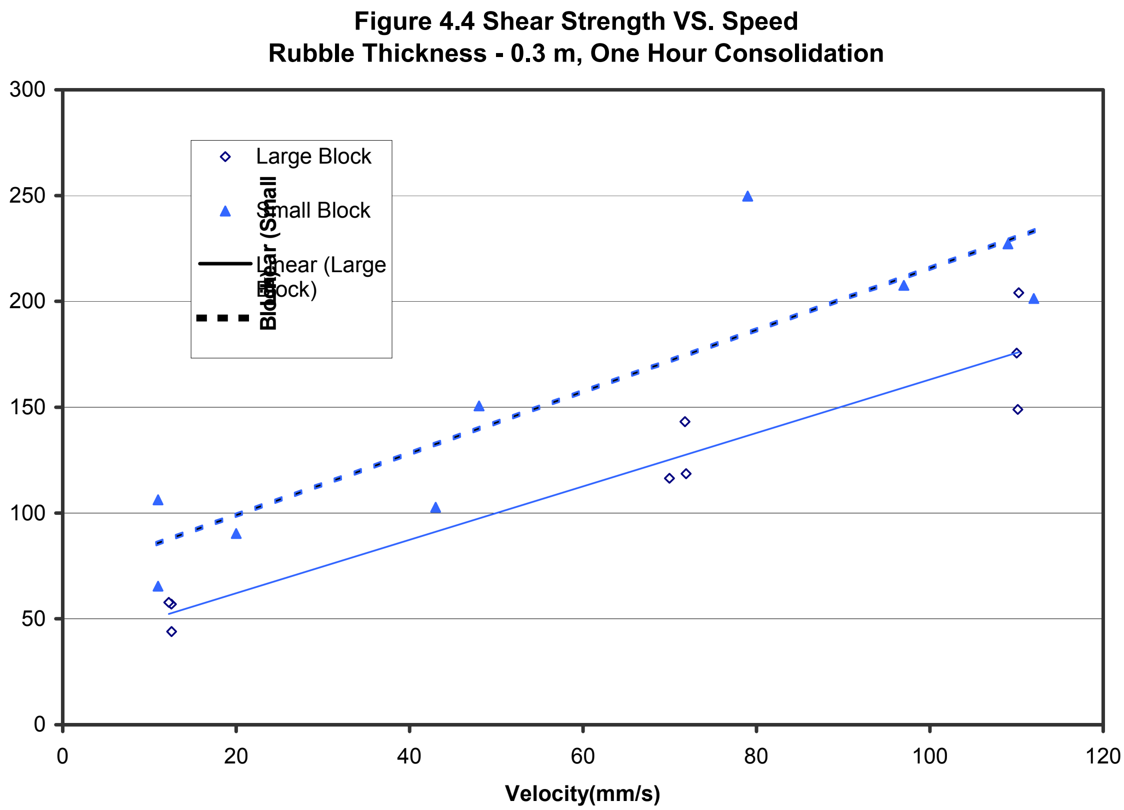


Figure 4.4 Shear Strength VS. Speed
Rubble Thickness - 0.3 m, One Hour Consolidation
Large Block
Small Block
Linear (Large Block)
Linear (Small Block)
0
50
100
150
200
250
300
0
20
40
60
80
100
120
Velocity(mm/s)

Figure 4.5 Shear Strength VS. Speed
Rubble Thickness - 0.4 m, Zero Consolidation

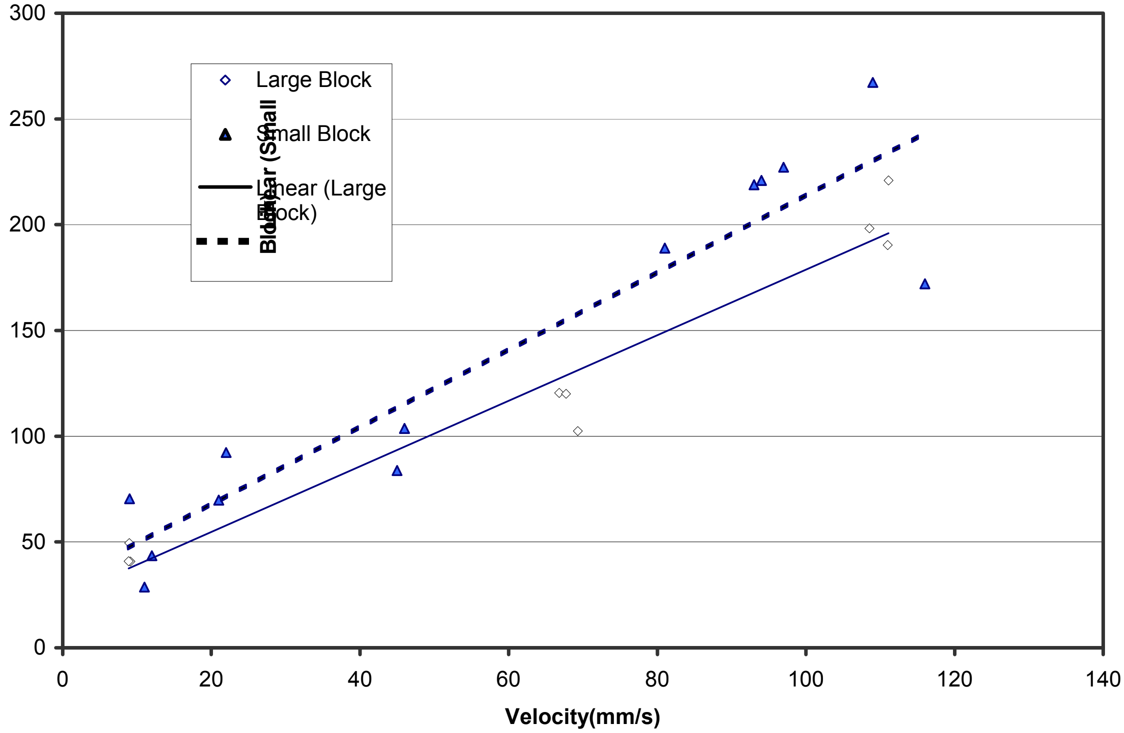


Figure 4.6 Shear Strength VS. Speed
Rubble Thickness - 0.4 m, One Hour Consolidation

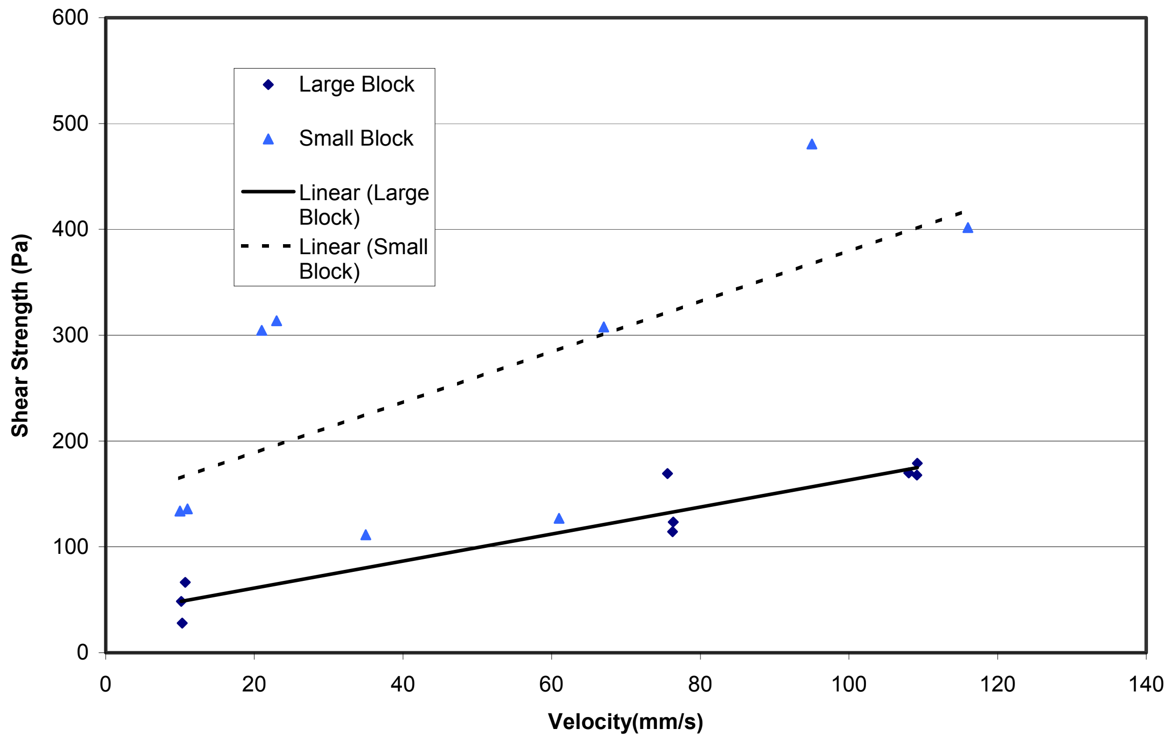


Figure 4.7 Summary of Shear Strength
Rubble Thickness - 0.4 m, Zero Consolidation

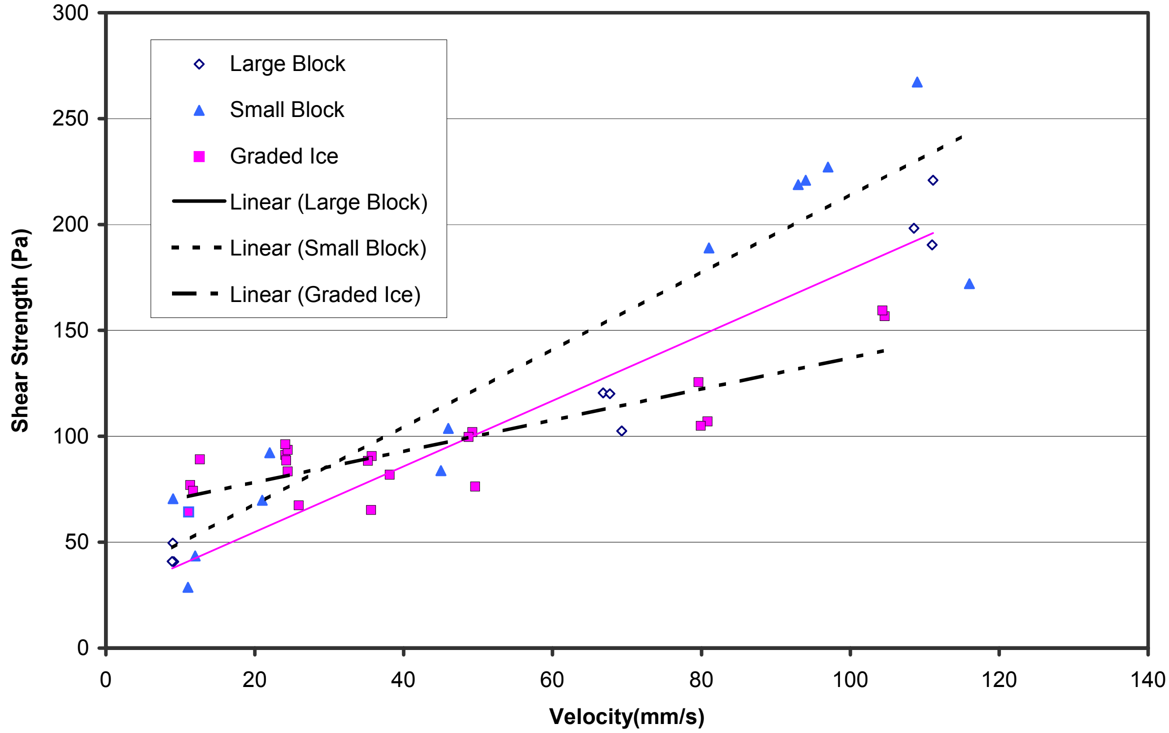


Figure 4.8 Friction Angle vs. Speed
Rubble Thickness - 0.4 m, Zero Consolidation

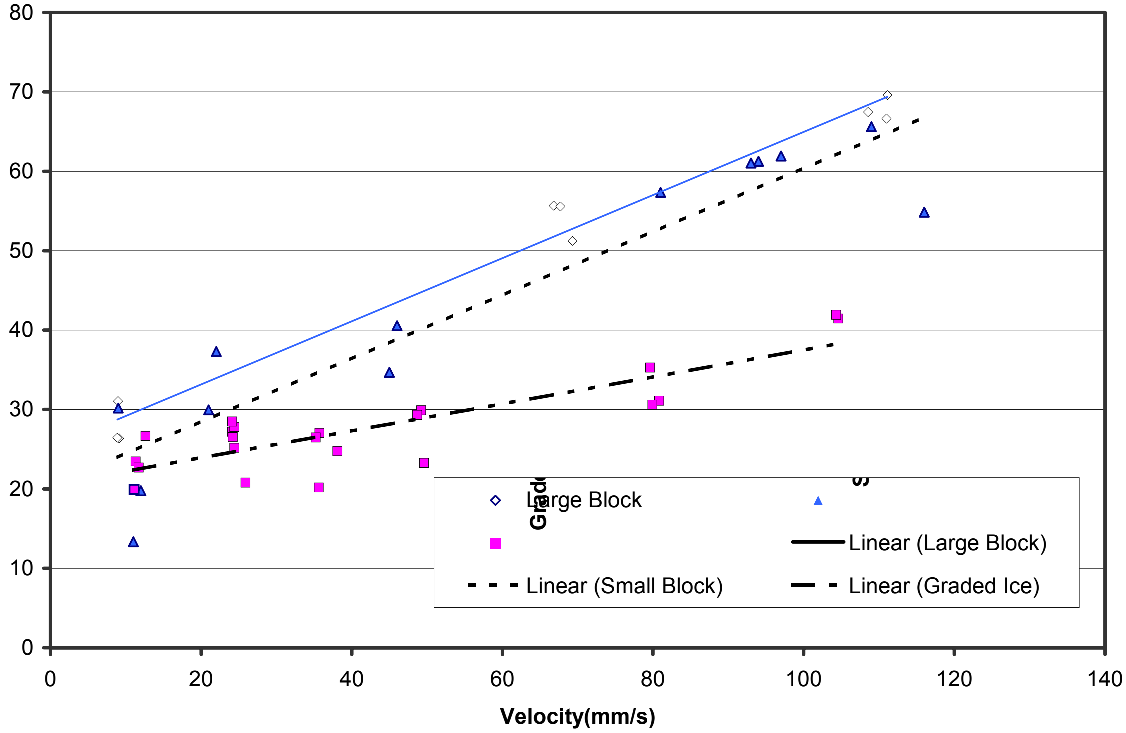


Figure 4.9 Phi from Punch Tests

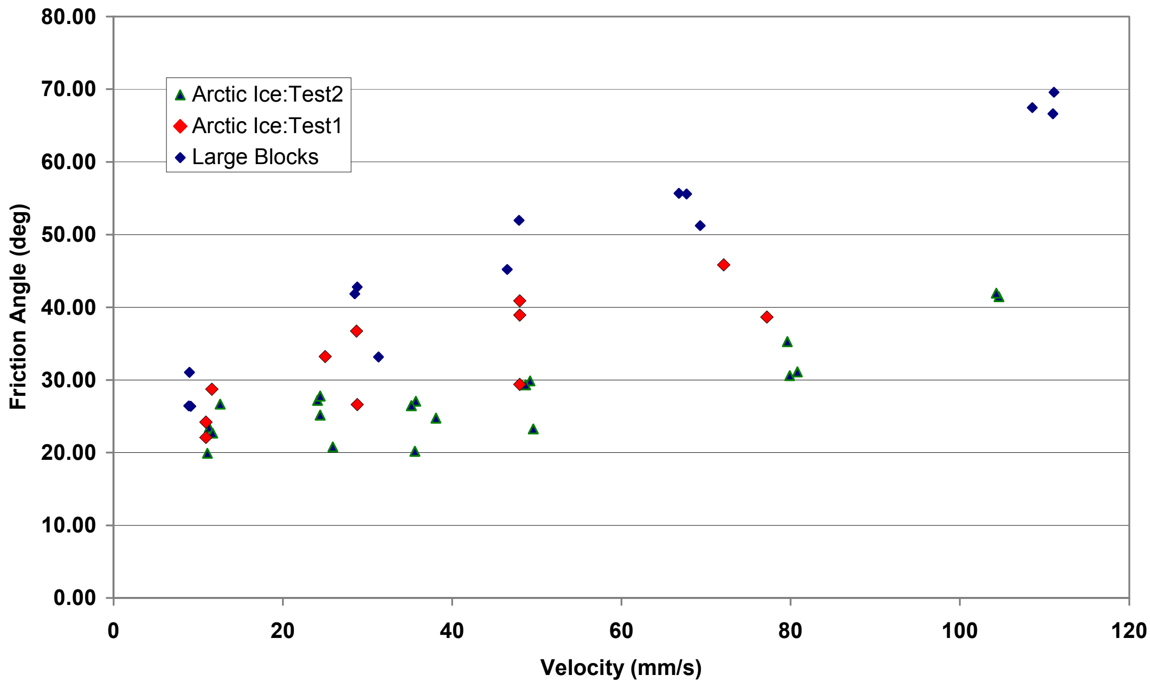
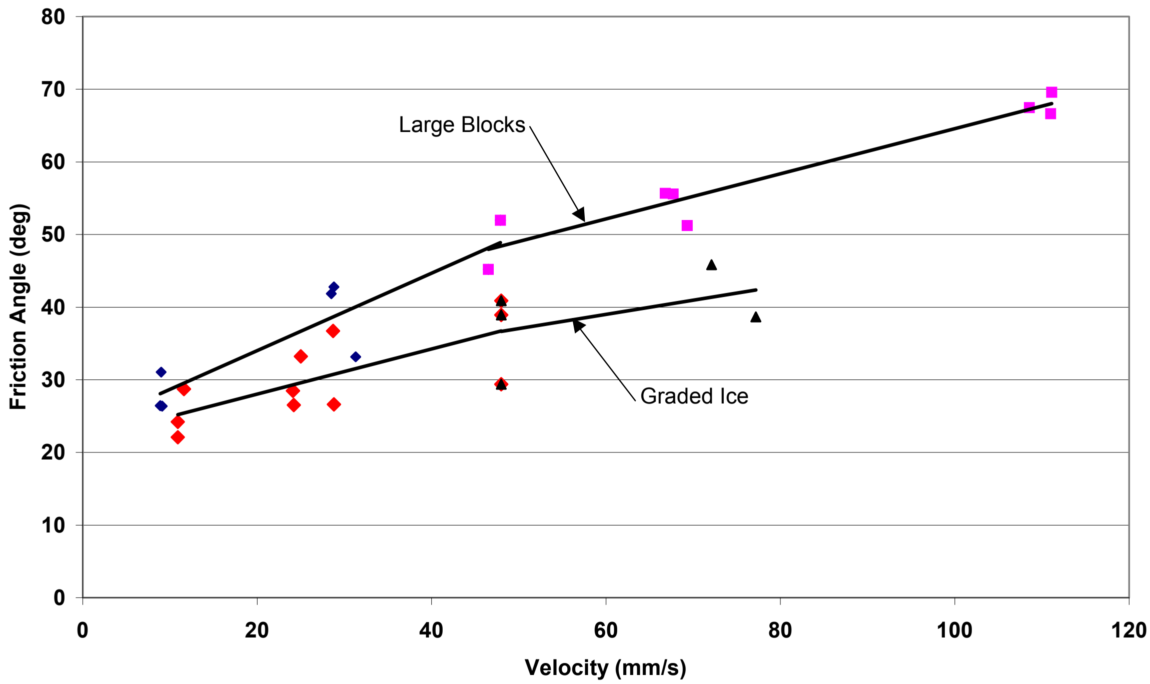


Figure 4.10 BiLinear Variation of Friction Angle



Chapter 5 Conclusions and Recommendations

5.1 Conclusions

On the basis of the tests carried out in the current project, and previous tests, a number of conclusions can be drawn. However, the additional tests have also prompted some additional questions, suggested new lines of enquiry.

A. There is clearly two different forms of behaviour that depend on platen speed. At higher speeds, there is significant particle motion along the failure planes that are much less well defined. At lower speeds the rubble fails along very clearly defined planes with minimal lateral disturbance of the ice particles.

B. The transition between the two forms of behaviour is in the range of 40 to 50 mm/sec. For the two sizes of blocks used to date, there does not seem to be any difference in this speed.

C. Consolidation of the ice results in an increase in the shear strength of the rubble. However, this effect becomes less pronounced as the rubble thickness increases and, at a rubble thickness of 0.4 m, the effect of one hour consolidation has virtually disappeared. Previous work with longer consolidation times has shown that the effect is noticeable, even at a rubble thickness of 0.4 m.

D. Even within the speed ranges associated with the two forms of behaviour, there is an increase in shear strength with platen speed. The effect of speed is largely independent of consolidation.

E. The effect of block size depends on the effect of consolidation. With no consolidation, the resulting shear strengths for small and large block sizes were generally the same for all rubble thicknesses. At one hour consolidation however, the shear strength for the larger blocks was lower than that of the original, small, blocks. As the additional strength due to consolidation is due to regelation between pieces, this is not surprising, as the number of such bonds will be greater with the smaller blocks.

F. The shear strength of the graded ice was substantially less dependent on speed than that on the single sized pieces. At low speeds, the shear strength of the graded ice was slightly higher than that of the two single sized strengths. At higher speeds, however, the shear strength of the graded ice was substantially lower than that of the single sized rubble ice.

G. Although friction angles have been reported for all tests, the observed behaviour at higher platen speeds suggests that the rubble is not behaving as a Mohr-Coulomb material and hence an internal friction angle may not be an appropriate measure of strength. However, the friction angle does increase with speed, even at the lower speeds.

H. For the rubble consisting of single sized pieces, the friction angle for the small pieces is slightly lower than that for the large pieces, the difference being consistently about 5°. The friction angles for the graded ice, however, are significantly lower than the other results. This may be attributed to a reduced propensity for mechanical interlock due to the range of piece sizes.

I. Finally, by considering the friction angles separately for the speed ranges associate with the two different forms of behaviour, it may be seen that the friction angle at lower speeds, where the behaviour exhibits classical shear plane failure, is more strongly dependent on speed that at the higher speeds.

5.2 Recommendations:

There are two important recommendations that are being made on the basis of the tests that have been conducted to date, and one that has been made previously.

A. The effect of size needs to be further investigated, both in the context of the results presented here, and in the context of mirroring the relative scale of ice rubble tested in field programmes, where the rubble pieces are larger in relation to the platen than has been tested in the laboratory to date.

B. The difference in behaviour that is observed at higher speeds needs to be further investigated. This behaviour is not observed in field tests, but the platen speed in field tests is much lower, in relation to characteristic rubble piece sizes, than in the laboratory. However, in rubble interactions with offshore structures, higher relative speeds are possible, especially in tidal regimes.

C. The plane strain test arrangement should be used to examine horizontal indentation of model rubble.

References:

Azarnejad, A., and Brown, T. G., 2001, "Ice Rubble Behaviour in Punch Tests". ASCE Journal of Cold Regions Engineering, Vol. 15, No. 3, September, pp135-153.

Azarnejad A. and Brown T.G., 1999. "Experimental Investigation of Ice Rubble Behaviour and Strength in Punch Tests", Report submitted to National Research Council of Canada, Ottawa, Canada.

Brown T.G. and Azarnejad A., 1997. "Experimental Investigation of Ice Rubble Behaviour and Strength in Punch Tests", Report submitted to National Energy Board (Canada), Calgary, Alberta.

Croasdale K.R. and Associates. 1996. " In Situ Strength Measurements of First-Year Ridge Keels for Interaction Models. Joint Industry Project for NEB, April 1996, 210p.

Heinonen, J., Määttänen, M., Høyland, K.V., Kjestveit, G. 1999 "Ridge Loading Experiments" Field Experiments in Winter 1999, Unpublished report for the LOLEIF Project, 2000, 73 p.

Leppäranta, M. and Hakala, R. 1992. "The Structure and Strength of First-year Ice Ridges in the Baltic Sea, Cold Regions Science and Technology, 20, pp. 295-311.

McKenna, R.F. Bruneau, S.E. and Williams, F.M. 1996. "In Situ Shear Strength Measurements of Model Ice Rubble Using a Punch Technique. The 49th Canadian Geotechnical Conference of the Canadian Geotechnical Society, Sep, 1996 St. John's Nf. pp279-286.