SMALL-SCALE PLANE STRAIN PUNCH TESTS

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ABSTRACT
This paper summarizes the results of recent freshwater ice rubble tests conducted at the University of Calgary. The tests were conducted to assess the parameters that affect in-situ punch tests of ice rubble and to identify the mechanics and hydrodynamics of the ice rubble failure process. A rectangular transparent sided tank allowed a visual observation of rubble behaviour and the associated mechanisms under plane strain test conditions. Three new rubble types were investigated and the results compared with those from previous testing. Differences in failure mechanics as well as strength properties have been noted in the results obtained for the different rubble types.

INTRODUCTION
The similarities of ice rubble to geotechnical materials has led to ice rubble being modeled as a Mohr-Coulomb material where the shear strength (τ) is composed of the cohesion term (c) and a friction, resulting from normal stress (σ) and friction angle (ϕ):

\[ τ = c + σ \tan ϕ \] (1)

There are, however, many assumptions required for Equation 1 to be applicable. The cohesion term is a function of freeze bonds between the ice blocks. Such bonds, as described are broken early in any interaction (Ettema and Urroz, 1989; Croasdale, 1995). Full frictional resistance cannot be mobilized until significant relative motion on the failure plane has taken place. As such, it is highly unlikely that the frictional and cohesional terms will act simultaneously. Many have reported that rubble exhibits strain rate dependent shear strengths (Prodanovic, 1979; Hellmann, 1984).

It is clear that both the initial and post yield behaviour of the rubble will be affected by aging, thermal conditions, block shape, initial stress conditions of the rubble and testing strain rate. Full-scale rubble testing is done in two ways; punch tests and direct shear. The plane strain punch test described below attempts to resolve the unknown physics such that the results could be related to the full-scale tests done in the field.

TEST SETUP
Testing was conducted in a 0.5 m × 0.9 m × 2.45 m transparent tank as shown in

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Figure 1. To prevent rubble motion at the ends of the tank, friction was increased by gluing rectangular blocks along the tank walls. The center of the tank was left smooth to allow the natural failure planes to develop.

![Equipment configuration diagram](image)

**Figure 1: Equipment configuration**

Load was applied through a rectangular platen, 25 cm by 50 cm, attached to a hydraulic ram. Displacement and load on the platen were measured using a potentiometer and a load cell. The test apparatus was placed inside a cold room (–1 °C) located in the Geotechnical Lab of the University of Calgary to maintain sub zero temperatures.

Tests were conducted by filling the tank with water and chilling it to marginally above freezing. Fresh-water rubble of the desired depth, up to 40 cm, was added to the water to create a floating layer of rubble. The refrozen top layer (consolidated layer) was cut with a saw around the base of the platen to allow an unobstructed failure plane. The platen was then pushed through the rubble; load, displacement and video were recorded.

**TESTING PROGRAM**

Four different rubble types have been tested. The small cubes were originally tested in 1997 and 1998 (Azarnejad and Brown, 2001). Three other rubble types were tested in the summer and winter of 2001–02. Table 1 lists the physical properties of each rubble type. The number of tests and testing variables for each rubble type are shown in Table 2.

<table>
<thead>
<tr>
<th>Rubble Type</th>
<th>Average Dimension (mm)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Cubes</td>
<td>20 × 15 × 7.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Large Cubes</td>
<td>35 × 35 × 15</td>
<td>0.648</td>
</tr>
<tr>
<td>Arctic Ice</td>
<td>20.5 (graded)</td>
<td>0.386</td>
</tr>
<tr>
<td>Big Blocks</td>
<td>100 × 150 × 25</td>
<td>0.526</td>
</tr>
</tbody>
</table>
### Table 2: Summary of Test Program

<table>
<thead>
<tr>
<th>Rubble type</th>
<th>Number of Tests</th>
<th>Speed (mm/s)</th>
<th>Rubble Layer Thickness (cm)</th>
<th>Consolidation Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Cubes</td>
<td>105</td>
<td>9, 45, 90</td>
<td>20, 30, 40</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>Large Cubes</td>
<td>76</td>
<td>9 up to 110</td>
<td>20, 30, 40</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>Arctic Ice</td>
<td>30</td>
<td>9 up to 105</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Big Blocks</td>
<td>15</td>
<td>9 up to 105</td>
<td>40</td>
<td>0</td>
</tr>
</tbody>
</table>

### RESULTS

The results of each test can be interpreted as two strength components; cohesion or friction. For the slow speed tests it has already been concluded that the tests can be interpreted as a Mohr-Coulomb material with internal friction angle (Azarnejad and Brown, 2001). Meyerhof and Adams proposed the following equation for the pull-out of anchors in frictional soils (Meyerhof and Adams, 1968), modified here for the buoyancy of ice rubble:

\[
\text{Peak load} - \text{buoyant force} = 2ch + \gamma h^2 K_u \tan \phi
\]

\( \gamma \) is the specific weight, \( K_u \) is the nominal uplift coefficient of earth pressure on a vertical plane through the footing edge, set to 0.95, and \( h \) is the depth of the anchor.

### Speed

Speed had the largest effect on the peak load as shown in Figure 2. The effect of speed can be separated into two categories shown by the bilinear lines. The first and second half of the lines has been designated slow and fast behaviours respectively. The transition point between slow and fast behaviours was located between 25 mm/s and 45 mm/s depending on the rubble type.

![Figure 2: Effect of Speed on Friction Angle for Different Rubble Types](image-url)
Slow speed tests were characterized by a trapezoidal plug being forced downward under the platen, Mohr-Coulomb failure, as shown in Figure 3. Initial failure occurred at the edges of the plug, in a region of approximately two to three ice blocks thick, and the surrounding rubble remained mainly undisturbed. After increased displacement, secondary failures would occur such as splitting up of the center of the plug also shown in Figure 3.

The fast speed tests showed a more complicated failure pattern than the slow tests as rubble failure was not as confined as in the slow tests. Compared to the slow tests, a larger area of ice, both under the platen and in the surrounding ice, was disturbed. The failure plug below the tests was triangular with the point facing down. The height of the triangular plug was about equal to the width of the platen. As the platen was moving down, one could see the development of a bulge at the bottom surface of the ice without a distinct plug being formed as shown Figure 5.

The difference in behaviour in the two speeds is also visible in the load displacement curves. The slow speed tests show a very rapid climb to the peak load then a drop to a plateau as the plug buoyancy is the remaining force (Figure 4). High-speed behaviour is very different from the slow speed. Figure 6 shows that there is often an initial spike when the platen strikes the rubble. This is followed by a slower increase to the maximum load and drop to a plateau. The plateau is reached as the triangle of rubble exits the base of the rubble layer. This gentle rise and drop in load support a progressive failure.

![Figure 3: Failure mode for slow speed test](image3.png)
![Figure 4: Load trace for slow speed test](image4.png)

**Consolidation time**

Consolidation times were tested for only the small and large cubes. Consolidation was achieved by allowing the rubble to cure in the tank while the room temperature was maintained at sub zero temperatures. In all tests the effect of consolidation was to increase the strength of the rubble. Freeze bonding between blocks at the contact points increased strength even though the water temperature was above freezing.
When comparing the behaviour of the two cubes, there was little difference in the results when there was no consolidation. The results after one hour consolidation do show some difference, with the behaviour of the smaller cubes being characterised by an increase in strength. This is consistent at all rubble depths. As the speed was increased, it was found that the strength for both consolidation times approached the same value. The large cubes showed very little change with consolidation time at the 30 cm and 40 cm thick rubble depths. At the 20 cm rubble thickness there was an increase on strength during the slow speed tests but high speed tests showed no change. This difference in behaviour may be due to the larger number of contacts between the small cubes. Also, the higher porosity of the larger cubes may cause less consolidation to occur.

**Rubble type**

Figure 2 shows that the change in behaviour due to speed occurred at 35 mm/s for the blocks and at 25 mm/s for Arctic Ice. The lower transition in Arctic Ice can be explained by the lower porosity and smaller voids. The reduced space for water flow causes increased hydrodynamic effects to begin at lower velocities. Figure 2 also shows that the strength of Arctic Ice was less than the strength of the two cube types as velocity was increased. Again, this must be attributed to the hydrodynamic effects, as a graded sample will provide a higher friction angle because of greater interlock between particles (Holtz, 1981).

The slow speed trapezoidal failure has two failure planes originating from the edge of the platen extending to the base of the rubble. There was a difference in failure plane angle for each of the rubble types tested. The small cubes had an average failure angle of 38.8°, measured between vertical and the plug failure surface, for 40 cm thick rubble with no consolidation. When the cubes had consolidated for one hour, the average failure angle was 30.0°. The reduction in failure angle suggests that the rubble is becoming more cohesive as a purely cohesive material would have a failure angle of 0°. The Arctic Ice had a failure angle of 23.4°, which is less than either of the cubes.
suggesting that this material is more cohesive and less frictional. The lower porosity and grading of Arctic ice would suggest more contacts between blocks.

The big blocks showed differences in the load displacement curve and in the failure behaviour as the size of the blocks caused a change in the failure mechanics. Figure 8 shows that the maximum load is achieved after a greater displacement. 120 mm of platen displacement is required compared with 60 mm for the other rubble types. Larger platen displacements are required to mobilize the friction between the larger blocks.

The big blocks showed no visible change in failure mode due to speed as in the other tests even though there was a bilinear slope in the load vs. speed graph. At all speeds, the trapezoidal plug would form. After continued displacement after the initial failure, the edges of the trapezoidal plug would fail causing a triangular plug to form (similar to the fast test in Figure 5). As the failure mechanism was similar for tests at different speeds, all the load displacement traces were similar to that shown in Figure 8.

The large size of the big blocks changed the aspect ratio of maximum block dimension to platen width. This caused an increase of the effective width of the platen thus changing the calculated $\phi$. Blocks would get confined under the platen and protrude on either side. The failure planes would no longer form at the edge of the platen but at the edge of the trapped blocks. The new, effective platen size, is the platen plus the trapped blocks on each side. The average effective change in platen width on each side, was 5.1 cm or approximately 0.3–0.5 the maximum block dimension.

Figure 7: Failure for Big Blocks

Figure 8: Load Curve for Big Block tests

**Temperature**

A third parameter was subsequently tested when the ice for one set of tests was stored in a chest freezer at $-30 \, ^\circ C$ before the test was conducted. All other rubble was stored at a temperature closer to $-1 \, ^\circ C$. Storage temperature was found to have a very large effect on the strength of rubble. While conducting the tests with the colder ice it was observed that when it was placed in the tank it would maintain near vertical free edges. This shows that the ice was forming much stronger bonds between blocks than the warmer
ice. The cohesive strength of the rubble stored at a colder temperature was much stronger than the other rubbles. A difference of approximately 10° was observed in the friction angles. As all other tests were conducted with ice temperature close to freezing, the results of these tests have been omitted from Figure 2.

CONCLUSION AND RECOMMENDATIONS
The combination of the visible failure planes and load trace resulted in very valuable information on rubble failure properties. It was found that the failure mode and load were very dependent on the loading rate. This was true with all rubble types. At slow rates a trapezoidal plug was formed below the platen; Mohr-Coulomb behaviour. At high speeds, hydrodynamic effects increase the load and change the failure mode to a local progressive failure defined by a triangular plug with the point facing down.

With more consolidation time or with ice rubble stored at a colder temperature before submersion in water, the failure plane angle was reduced and the friction angle was increased indicating that the material is becoming more cohesive due to stronger freeze bonding.

The big blocks required double the platen displacement to mobilize the friction in the rubble. As well, the large block size to platen width ratio effectively gives a larger platen size due to blocks be trapped and overhanging the platen sides.

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REFERENCES