Simulating and Testing Ice Screw Performance in the Laboratory

Final Report

16. 622

Spring 2003

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13th May 2002

Abstract

This project replicated natural ice formations in the laboratory by testing a set of methodologies of ice manufacture and analyzing the ice specimens obtained through a series of prescribed measurements. Once repeatable ice formation was achieved, the variables affecting ice screw safety were tested in the simulated ice.

Ice screws are protection devices that allow climbers to anchor themselves to ice. This project was a response to the current lack of any controlled testing procedure for ice screws, and the perceived margin for improvement of ice screw design and usage in the field. This project is of value to the technical and the climbing community because it will create a methodology for making 'climbing ice' types in the lab and provide data on current safety standards of ice climbing equipment. This study will reduce the failure rate in ice climbing by being the first step towards the improvement of such protective equipment, and in educating climbers about the limits of their equipment and how to use that equipment most effectively.

The conclusion drawn from the data obtained in Stage 1 was that more research should be done into how different ice types can be differentiated. The density test was the only statistically significant quantitative method for describing different ice types. The main conclusion from Stage 2 was that raising the loading rate lowers the failure loads. Climbers should therefore concentrate on employing methods for reducing the loading rate on ice screws in the event of a fall.

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1. Introduction

1. 1 Background

Over the past 10 years, ice climbing has grown tremendously in its popularity as a sport. Ever since Yvon Chouinard introduced the first rigid crampons and curved ice picks in the late 1960's, climbers have been refining techniques and developing equipment in order to push the limits of ice climbing (see Figure 1).

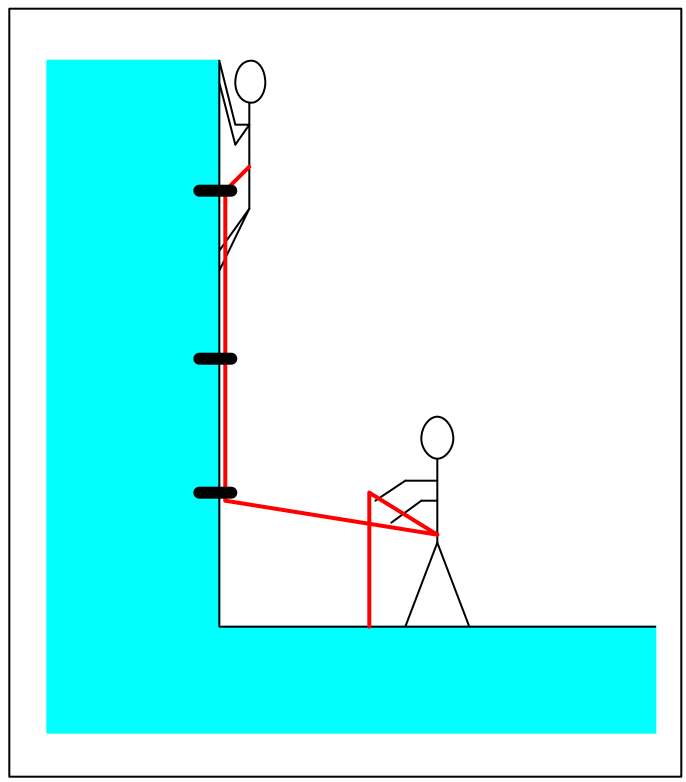


Figure 1: Illustrating a climber on an ice face*

Figure 2: Showing how ice screw protection works

Figure 2 shows how the ice screw protects a climber on the ice. As a climber ascends the ice face, ice screws are placed in the wall at intervals along the way. The frequency of placement depends on the competency and confidence of the individual climber.

* photograph taken by Luca Marinelli, exhibited courtesy of project advisor, David Custer.

The belayer at the base of the climb pays out rope to the climber above; if the climber falls, the fall will only be as far as the highest ice screw and the belayer locks off the rope and prevents it from paying out further, thus arresting the fall.

One of the current limitations on ice climbing is the strength of the interface between anchors that the climbers use and the ice wall. Current research into better protection is based on anecdotal evidence and lacks a controlled methodology for test or evaluation. Ice screws are the main protection type; thus, for the purposes of this investigation, the focus is solely on ice screws.

Ice screws are pieces of climbing safety gear that are used as anchors on a route. This route can be led (when the climber places his own protection on the route) or top-roped (a rope anchored at the top of the climb). The climber is then attached to the screw by a carabiner through the hanger and is thus anchored to the climbing face. Figure 3 shows an ice screw.

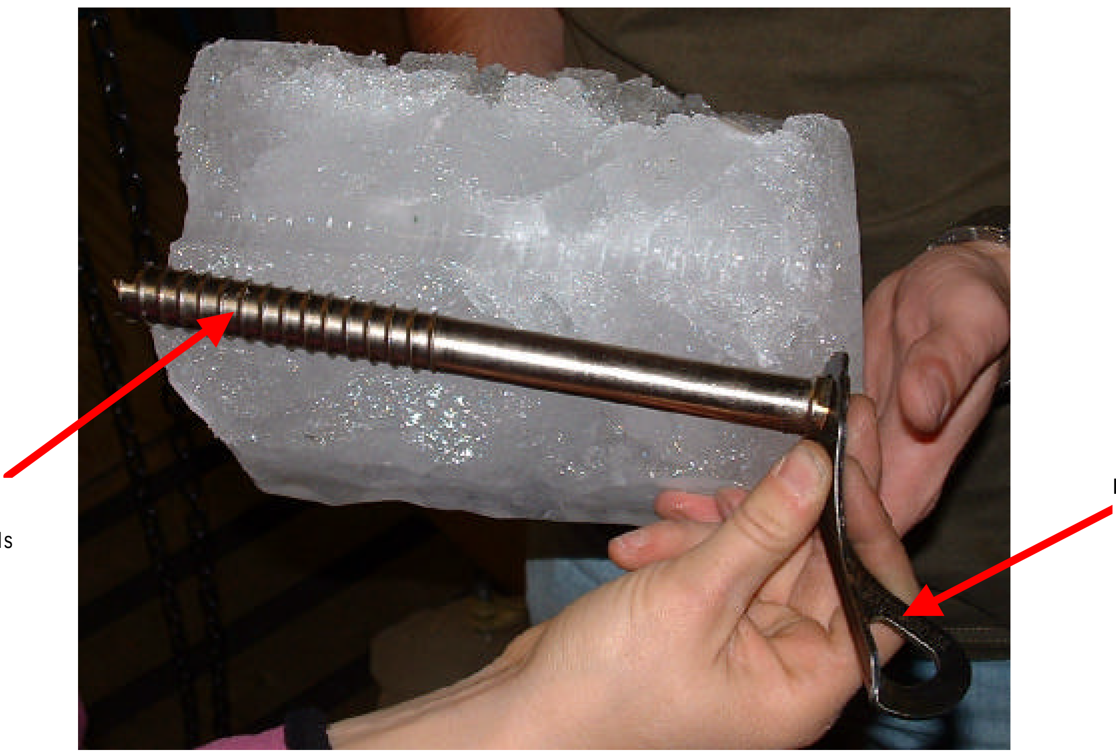


Figure 3: An ice screw

The ice screw itself is a hollow screw that is turned into the ice by use of a ‘hanger’ on its end. The screw first ‘bites’ the ice with a set of sharp, beveled teeth; as it is turned, the ice is forced out through the center of the hollow screw. In order to reduce friction, both the inside surface and outside threaded surface of the screw are machined to be smooth. The screw is usually in the range of 10-22 cm long and has a diameter in the range of 15-17 mm. The hanger is typically around 8 cm long. Screws can be made from steel or titanium.

Ice screws provide effective anchoring if placed properly, but, like all protection devices, are subject to the changeable nature of the ice environment. Proper placement is defined as placing the screw in good ice and at an orientation that allows the loading to be held by the screw threads so the load path runs the length of the screw.

The essence of good ice protection is speed and reliability. The gear must be placed in tens of seconds to minimize climb-time, and thus fatigue. It must also sustain the forces produced in the event of a fall (around 10 kN).

Existing research is lacking in the area of ice protection technology. There a few documented tests in the public domain, but these tests have not been sufficiently controlled. The statistics from these tests, notably the Harmston, Luebben study in 1997[1] and the study commissioned by Black Diamond,[2] concluded that there is room for improvement in ice protection performance.

There have been numerous papers into the study of ice mechanics and also into the study of the rheological nature of ice. This forms the basis of the literature review in Section 3.

1. 2 Previous Work

There have been only two published studies directly relevant to the ice screw testing. The first study carried out 6 years ago was performed in field. The second, more similar to this project, was carried out in the laboratory on uncharacterized ice that was not fresh but simply re-filled with water and re-frozen. Neither of these studies controlled the ice in which the ice screw was tested. This project controls the ice test bed and is an improvement on these previous studies. Further details of these projects can be found in Section 3.4.

1. 3 Summary of Project

The motivation for this project is twofold. First, the poor performance of ice screws in existing tests, and second, the lack of repeatability of the existing tests. The development of a standardized testing procedure will enable improvement of ice protection in the future.

The project goals are, first, to produce a realistic simulation of the ice in the lab, and, second, to test the factors that affect the safety of ice screws and their placement. In order to realize this project, the procedure was:

1) Investigate and understand ice types and their formation.

2) Develop a method of repeatably replicating ice and produce two different varieties of ice herein referred to as ABS1 and ABS2 (standing for Alziati-Bennett Standard).

3) Develop a controlled methodology for testing the factors that affect the safety of the placement of ice screws.

Successful completion of the primary goal will permit controlled testing and evaluation of ice screws and will allow the industry to initiate standardized testing of ice protection,

1. 4 Value to Technical and Climbing Community

This project is of value to the technical and the climbing community because it created a methodology for making "climbing ice" types in the lab. Currently, there is no data available on repeatable ice formation processes for testing ice-climbing equipment in the public domain. If ice is effectively simulated in the laboratory, the industry will be closer to setting safety standards and thus providing safer protection for climbers everywhere. An inexpensive, reliable and realistic lab-based testing method for ice protection would give strong support to the development of ice protection beyond its present state.

If the first part of the experiment is fulfilled, then this project will go on to provide data on current safety standards of ice climbing equipment. It is also hoped that this study will reduce the failure rate in ice climbing by being the first step in educating climbers about the limits of their equipment and how to use that equipment most effectively.

2. Statement of Project

The Primary Hypothesis is:

The structure and morphology of different types of ice formations can be characterized and simulated in a lab to provide a "test bed" useful for assessment of ice screws.

The Secondary Hypothesis is:

If the above hypothesis is true, then using the simulated ice, the variables affecting screw placement safety can be determined.

The objectives are then, first, to develop a repeatable means of reproducing ice in a lab and to characterize this ice using rheological data; or to understand why ice cannot be simulated in the lab, and second, to use this ice model to test simulated falls on ice screws in a manner closely related to climbing conditions.

The success criteria that will be used to measure the project are:

1 a) If hypothesis 1 is true, then success is characterizing the critical rheological properties of ice.

b) If hypothesis 1 is false, then success is identifying why ice cannot be made successfully.

2 a) If hypothesis 2 is true, then success is the development of a test for ice screw safety that produces consistent data and repeatable data.

b) If hypothesis 2 is false, then success is identifying why ice screw performance cannot be characterized.

3. Literature Review

The three topics of the literature review cover: the understanding of ice, ice testing results, and ice screw testing and studies.

3. 1 Understanding Ice

This section covers ice structure, ice formation, and the micro-mechanics of ice failure

3. 1. 1 Ice Structure

Ice is close to melting at the temperatures at which it is encountered in climbing (around 0º, according to the Harmston and Luebben study[1]). As such, it is a 'high temperature' material that exhibits a wide variety of behavior that is dependent on a number of factors. Ice can creep with little applied stress, or it can fracture in a brittle manner. Thus, classical solutions do not work for analysis of ice; it is neither a 'simple elastic' nor an 'elastic/plastic' solid. Instead, specific methods for its characterization must be undertaken.

According to Schulson[3], ice has 12 different crystallographic structures and 2 amorphous states. The particular structure formed most commonly in nature is the I_h-type. This is formed by simply freezing water and has a hexagonal structure (see Figure 4).

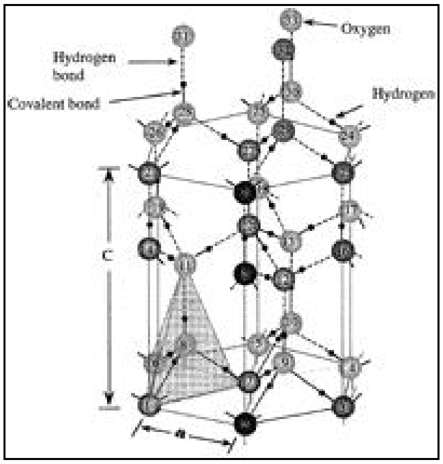


Figure 4: A schematic crystal structure of I_h ice

The oxygen atom is strongly covalenty bonded to the 2 hydrogens to form a single water molecule, but, when frozen, the water molecules themselves are bonded weakly by hydrogen-bonds. Vacancies in the structure are predominantly point defects. It is these, along with the dislocation density (the number of grain boundaries per unit volume), that determines the characteristics of the ice. The microstructure of the ice depends on its mechanical-thermal history. The mechanical-thermal history of the ice was especially important in stage 1 of this project because it was found that the initial condition of the ice gave rise to different behaviors when subjected to a compression test.

3. 1. 2 Ice Formation (morphology)

There are 3 main ways of forming natural ice:

1. Heterogeneous nucleation at the surface of a slowly flowing water body.
2. Nucleation of frazil (Fine spicules, plates or discoids of ice suspended in water) particles that appear in a fast flowing, supercooled water masses.
3. The freeze up of snow or atmospheric ice nuclei falling into the water.

These starting points for ice formation were considered in the context of producing ice in a laboratory.

3. 1. 3 Micromechanics of Failure

According to Wu & Niu[4], the main reason for ice failure is due to impurities at grain boundaries disrupting the overall structure. These impurities initiate early melting and microcracks. The grain structure and orientation also affects the failure mode. This information is important to how the macroscopic ice structure can be controlled in this project (by addition of impurities in ABS2 for example).

3. 2 Ice Testing Results

This section of the literature review focuses on the methods used to characterize the engineering properties of ice.

3. 2. 1 Compressive Strength

The benchmark for compressive strength is set by uni-axial load tests on specimens in laboratories[5]. There have been numerous studies carried out on the ice *in situ* but analysis of these tests was hampered by the complex stress states set up within the ice.

Typical values for the range of compressive strength are from 0. 5 – 10 MPa. The mean value obtained in this experiment was 0. 5 MPa (see Section 5. 1).

3. 2. 2 Flexural Strength

Flexural strength is generally lower than the compressive strength for ice and typically ranges from 0. 5–3 MPa. It should be noted that the temperature up to –5ºC did not influence the flexural strength of the specimen. This is noted to be a test that must be set up in extremely carefully controlled conditions. It was deemed that replicating these conditions for this project was not a viable option.

3. 2. 3 Ice Rheology

The stress-strain behavior of ice is important to understand as it has relevance to any study involving ice as a working material. [5] In a general sense, ice is described as a viscoelastic material. The simple spring dashpot model for ice is shown in Figure 5 below. This model attempts to simulate the four deformation mechanisms of ice:

1. Elastic deformation due to atomic bonds changing length.
2. Delayed elasticity due to sliding at the grain boundaries.
3. Viscous deformation due to dislocation movement within grains.
4. Deformation due to microcracks in the ice.

The total strain of the ice is usually thought of as the sum of all these components. This model allows for both the creep of the ice and the ductile to brittle transition, as strain rates are increased. The fourth point is the most important in relation to the project as the ice screw itself initiates many microcracks, and the primary reason for ice failure is the propagation of those cracks.

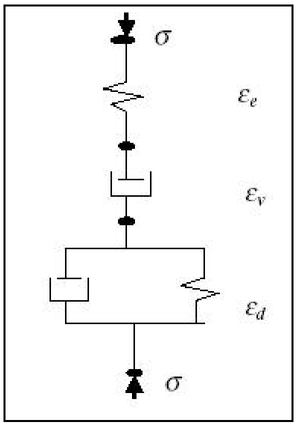


Figure 5: A spring and dashpot model of ice. [6]

3. 2. 4 Temperature Dependency

It has been shown that, at temperatures up to –5ºC, the flexural strength of the specimen is not influenced by temperature. [5,7] However at temperatures near zero, it was the impurities at the grain boundaries that induced melting which meant that even the flexural strength of thick ice was zero. This temperature dependency is important for the project as this indicates a marked change in behavior around the temperatures of interest.

3. 3 Making Ice

Information on the making of the ice was gathered, via email, from a current expert in the field of ice mechanics, John Dempsey. [7] Full details on 'how to make (perfect) ice' is found in Appendix A. Appendix A gives information on test apparatus insulation, tips on repeatable crystal growth (such as the use of existing frost particles to nucleate ice grains in the specimen), and it also gives advice on how to allow for the expansion of the water on freezing. This method was used to produce one ice type. The methods for making other types of ice were investigated in stage 1 of the project.

3. 4 Ice Screw Studies

3. 4. 1 The Harmston/Luebben Study

Harmston and Luebben[1] conducted tests that consist of placing ice screws into a natural ice formation and dropping a 185 lb weight from various heights, while statically attached to the protection point, giving forces of between 8 kN – 12 kN. The results from this test show that the screw ripped out of the ice 7 out of 12 times. A variety of variables were tested, including screw angle and screw length. The tests suggest that a downward angle for the screw is most effective and that a longer screw is more likely to hold than a shorter screw. The main conclusion drawn from the test was that ice conditions are so variable that it is difficult to accurately predict the holding strength of ice screw placement.

A critical examination of the test conditions suggest that many independent variables, including temperature, sun exposure and ice quality, were not controlled. Also, the uncontrolled method of dropping a weight onto the ice screw had no control over the strain rate.

3. 4. 2 Black Diamond Internal Study

Black Diamond Equipment has made its own investigations into ice screw effectiveness. [2] The tests consist of placing ice screws into an ice cell and then loading these cells in a Universal Test Machine. The ice cells were constrained by a steel container and prepared using untreated tap water. Freezing of the cells was at around –10ºC and the whole process took about 72 hours. Ice cells were regenerated 20 times by simply filling in the damaged hole and refreezing.

It was found in this study that the ice screws tested failed either by levering the hanger off the screw head, by breaking of the screw shaft, or by pulling the screw out of the ice. It was also found that the screw placement angle was a significant factor in how much load the ice screw could withstand.

The limitations on this study are the unpredictable and variable nature of the ice cells used for testing. The cell composition was not tightly controlled and regeneration of the cell is not consistent.

3. 5 Summary

All aspects of the literature review were taken into account during the development of the project. The experimental method used in the Black Diamond Study was used as basis for improvement in this project. The factors, identified in the literature review, that affect the behavior of ice were considered in this improvement.

Since temperature was not a variable investigated, it was held constant at a value below -5ºC in order that the ice would retain its brittle behavior. The Harmston/Luebben study identified screw placement angle as a significant variable affecting the amount of load a screw can support, thus the trends that they observed were investigated.

4. Description of Experiment

4. 1 Experimental Overview and Scope

To be able to test both hypotheses, the experiment was divided into two stages. The first stage consisted of experimenting with different types of methods for manufacturing ice and then characterizing each ice type produced. Stage 2 focused on using the method for producing different ice types to test different variables that affect screw placement safety.

4. 1. 1 Stage 1 – Characterization of ice

The aim of this stage was to produce two different ice types (ABS1 and ABS2) with distinct characteristics and be sure that the specimens would consistently have the same characteristics. ABS1 was designed to be the "good ice", whereas ABS2 was intended to mimic one of the kinds of "bad ice" ice climbers encounter. The test matrix used for this stage is shown in Figure 6.

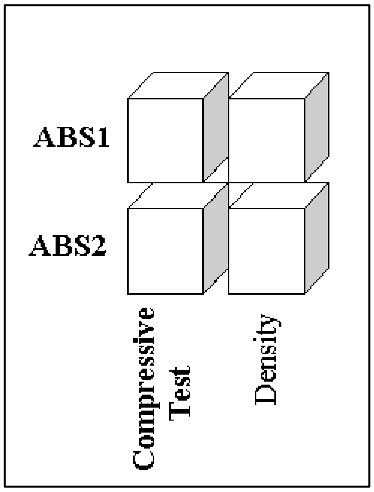


Figure 6: Stage 1 test matrix.

First, different recipes to produce several different ice specimens were investigated. Specimens were frozen in containers made from 16 cm diameter PVC tubing cut to a height of 16 cm. A sheet of strong flexible plastic, cut to a size that would overlap the edges of the tube's base, was taped to one end of tube. To ensure a watertight seal the bottom was covered using a latex rubber glove that was also taped into place. This not only gave an ice specimen with a smooth bottom surface finish (due to the plastic sheet) but also made extraction of the ice specimen a quick and easy process. Extraction of the ice required only the removal of the temporary plastic sheet base of the tube and then submersion in a stream of running water to loosen the ice from the tube walls. The only drawback to this method was the necessary individual setting up of each specimen tube.

The method for producing ABS1 was freezing normal tap water to produce the most perfect ice possible.

A greater focus was placed on finding a method for producing "bad ice" or ABS2. The different methods attempted for making ABS2 were:

Method 1: Made using a mix of crushed ice, grit and gravel. The thickness of each layer varied but overall there was a homogeneous spread of each component. The vessel was then filled with water, taking care not to disturb the crushed ice/grit structure by pouring in water at a slow rate and pouring it down the sides of the vessel.

Method 2: Made using dry sand (Multipurpose Play Sand, mesh 200). Construction was in the same manner as Method 1. However this sand was laid in 30g samples in between 500g of ice.

Method 3: Sand was laid in 60g samples in between 500g of ice in a similar way to that described in Method 1.

Method 4: Sand was laid in 60g samples in between 250g of ice in a similar way to that described in Method 1.

Method 5: Made using 50% carbonated water and 50% normal tap water and then frozen in the normal manner. The carbonated water was poured into the container first and then tap water was added making sure the final solution was homogenous.

Method 6: Made using 25% carbonated water and 75% normal tap water in the same manner as that described in method 5.

Figure 7: Pictures of ABS1 (left) and ABS2 (right).

A large number of specimens of ABS1 and ABS2 were then produced. Before any testing could commence, each specimen had to be prepared. Generally, most specimens contained a number of minor surface cracks. The top of the sample open to the air, was not always smooth and flat owing to internal stress build up in the later stages of growth when the tube itself was frozen. To rectify this problem, specimens were prepared by cutting off the top slice on a bandsaw. A slice was also cut for the impact testing.

The specimen prototypes produced using the above methods were then tested under a compressive test. Each ice specimen was then tested under compressive load as shown in Figure 8. A fixed displacement rate of 0.508 mm/s was used in the MTS machine. The load was measured by a load cell and recorded onto the computer.

The density was also measured, and some impact testing was also performed. The density calculation was carried out using a scale to measure the mass. The volume was found from measuring the height and diameter of the specimen after preparation.

The impact testing consisted of dropping a solid steel ball, weighing 0.1kg and with a diameter of 65 mm, from a fixed height of 1 m onto the flat surface of the ice specimen. The indentation on the surface was then measured. The results of this test were judged inconclusive as the surface indentation was too small to differentiate between individual tests.

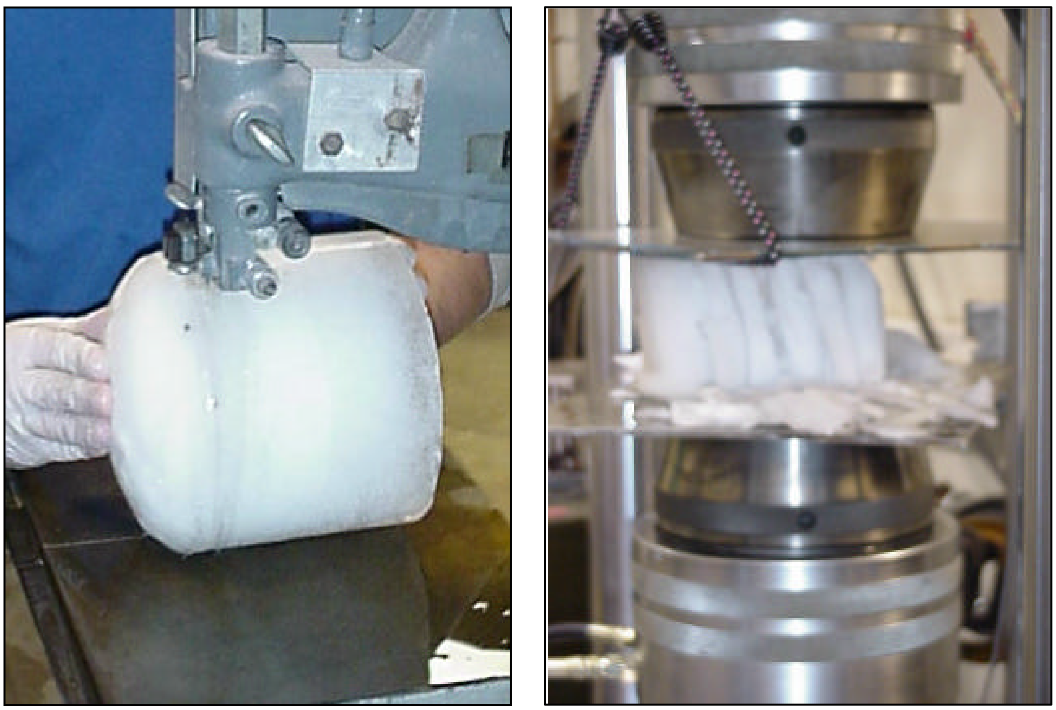


Figure 8: Preparing ABS2 for testing (left) and ABS2 being tested (right).

Based on the results of the above tests one method was then selected for the production of the official ABS2. Selection criteria were:

1. Largest difference between results for compressive tests.
2. Ease of production.

Even though Methods 3 and 4 produced ice with much larger mean compressive strength than ABS1, the production method was so labor intensive that it was not practical on a large scale. Method 5 produced an even lower mean than Method 6.

However the high proportion of carbonated water in the specimen meant that, often, large air pockets would develop, rendering that specimen useless. After consideration of all these factors, Method 6 was selected for the production of ABS2.

4. 1. 2 Stage 2 – Ice Screw Testing

The aim of this stage was to place ice screws in the different types of ice and investigate the factors which influence the failure of the ice and ice screw interface. The variables investigated here were ice type, screw placement angle and loading rate as shown by the test matrix in Figure 9. Figure 10 shows the definition of screw placement angle, the variable in the third dimension of the test matrix.

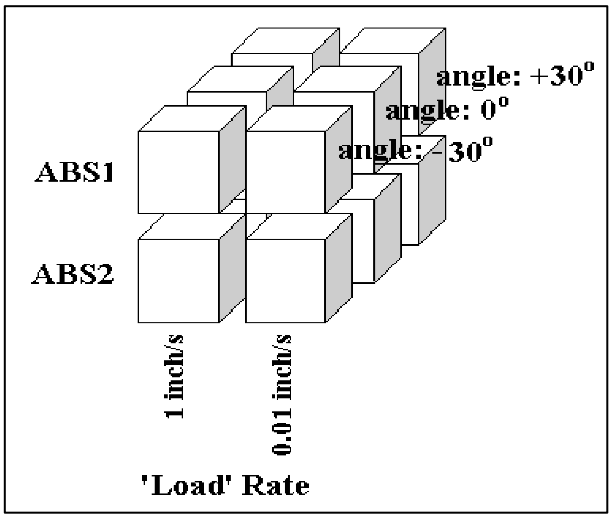


Figure 9: Stage 2 test matrix.

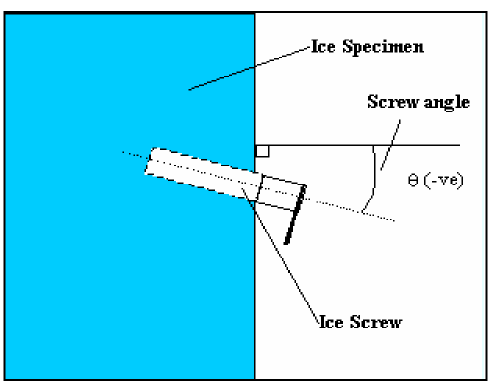


Figure 10: Schematic of screw placement.

This stage required larger samples of ABS1 and ABS2. This time, PVC containers 30 cm in diameter (internal), 40 cm in height and 15 mm thickness were used. The container walls were lined with large plastic bags. The bags were standard trash bags and were taped into place using duct tape. The seal of the bags to the tubes was not airtight to allow trapped air in the tube base to escape when the vessel was filled. Importantly, these specimens were made in the freezer and not moved until completed. They were filled with a hose and left for a period of days to freeze slowly. Samples were made as described in Section 4.1.1. This method allowed both ends of the ice specimen to be used by simply removing the plastic sheeting from the bottom.

As can be seen in Figure 11, each specimen was frozen with a plastic tube inside so as to reduce the internal stresses. When the top surface of the ice freezes, the remaining water continues to freeze and expand, if left unchecked this causes a build up of pressure under the top surface, which would lead to cracking. The tube allows water to be pushed up and out above the top surface as the interior expands.

Before experimenting commenced, tests were carried out to determine the length of specimen required so that each end of ice specimen could be used while remaining structurally unaffected by the experimentation on the other end. The size of each ice specimen in stage 2 made their construction an extremely laborious process. Having determined the length of specimen and corresponding length of ice screw required in order that both ends could be used for testing purposes, the testing time was effectively halved. Once the specimen was frozen, the plastic bag over the base could simply be ripped off and an ice screw could then be screwed in to both ends.

The ice screws used in the experimentation were Black Diamond Turbo Ice Screws 13 cm in length. This size was chosen as longer screws would have been too long for the 'infinite' ice surface to be effectively modeled within the confines of the chosen model.

Once the ice specimen was ready, an ice screw was screwed into it at the appropriate angle. The specimen was then strapped to a rig mounted on the MTS machine and the ice screw was pulled down. The ice was left in the PVC tubing throughout testing in order to effectively model the 'infinite' ice wall surface.

Figure 11: ABS1 sample for stage 2 testing.

The test rig was built using steel uni-struts as shown in Figure 12. The whole jig was about 90 cm in height, 40 cm wide and 25 cm deep. The thickness of the uni-struts used was 40 mm to be able to withstand the magnitude of the load without significant deformation. The whole gig was then assembled firmly to the MTS machine. In order to counteract the torque of the MTS machine pulling down on the ice screw, the gig was braced using a steel ratchet and pulley system pulling in the direction opposite to the applied load.

The ice screw was then attached to the arm of the MTS machine, which was set to pull at the desired load rate. The load on the screw was recorded by a load cell and logged on to a computer.

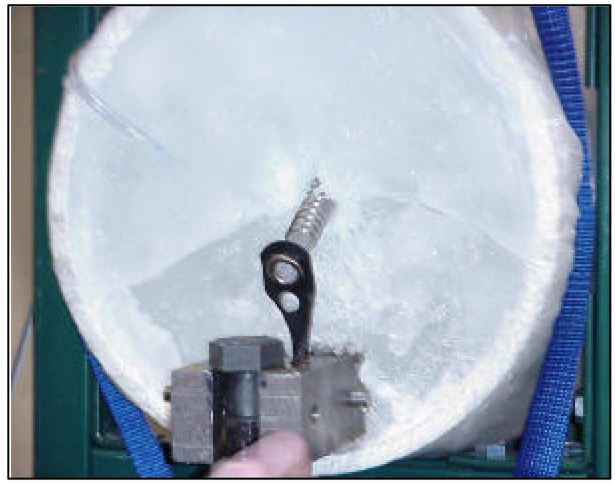
 

Figure 12: Test rig setup (left) and ice screw being pulled (right).

4. 2 Data Analysis and Error Mitigation

Data was logged using a load cell in both stage 1 and stage 2. In stage 1, data was transmitted at a frequency of 4 Hz, whereas in stage 2, data was taken at 500 Hz. The number of data points recorded was close to 500,000. This data was reduced and plotted using Microsoft Excel, and the value of compressive strength for each test was read off these graphs.

The measurement errors in the load cells were minimal. The specifications of the two load cells used can be found in Appendix C. A maximum error of ± 5N was measured, and this was regarded as negligible, considering the large amount of data scatter due to the natural random behavior of ice.

The degree of scatter in the data for each test was measured using a standard deviation calculation. This was compared to the mean to have a measure of the uncertainty and limits either way of the mean value. The one-tailed f-stat test was used to compare data sets, such as when the data set of ABS1 was compared to that of ABS2. This test compares the spread of two sets of results obtained, and produces a numeric probability of the chance that the means of the two samples are different. Once again calculations were performed in Microsoft Excel.

5. Stage 1 – Results & Discussion

5.1 Selection of ABS2

The methods described for producing prototypes of ABS2 in Section 4 were all tested. Some methods were investigated to a greater extent than others because they proved to be easier than others. Methods 2, 3 and 4 were very labor intensive and it was judged that they were unsuitable for producing specimens in a larger scale. Method 1 was a little less labor intensive but was not tightly controlled and produced results with a large standard deviation. Table 1 shows the mean compressive strengths and standard deviations for each method investigated.

Table 1: Mean compressive tests for all the methods

Ice Type	ABS 1	ABS2					
		Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
Mean Compressive Strength (N)	9792	6693	18953	19838	20547	6028	8012
Standard Deviation (N)	2837	2929	3960	2076	9015	1859	2749
Number of Tests performed	9	3	3	3	2	5	10

It is observable from the table that Method 5 appears to be better than method 6 as the mean compressive strength is lower than the one for method 6 and ABS1 and the standard deviation is also lower. However, while making specimens using Method 5 several of them had to be discarded because of huge air pockets just under the surface layer which made them unsuitable for testing. The five specimens that were tested were cut at a height below the air pocket. Unfortunately it wouldn't have been possible to cut the larger specimen for testing in stage 2, so it was decided that Method 6 was the most suitable for stage 2.

5. 2 Density Test

The density test, which was described in Section 4 yielded the following mean results:

Table 2: Mean value and standard deviation for density.

Ice Type	Mean Density (kg/m^3)	Standard Deviation (kg/m^3)
ABS1	913	0. 78
ABS2	804	31. 8

The F-Stat test indicated a 97% probability of ABS1 being different to ABS2. This is due to the fact that the standard deviations are significantly less than the mean value for density. It is noticeable that the standard deviation for ABS2 is much greater than that for ABS1. ASB2 samples would occasionally have a slightly larger air bubble close to the surface. This is due to the surface of specimen freezing before the core and providing no escape route for the bubbles which accumulate just below this surface.

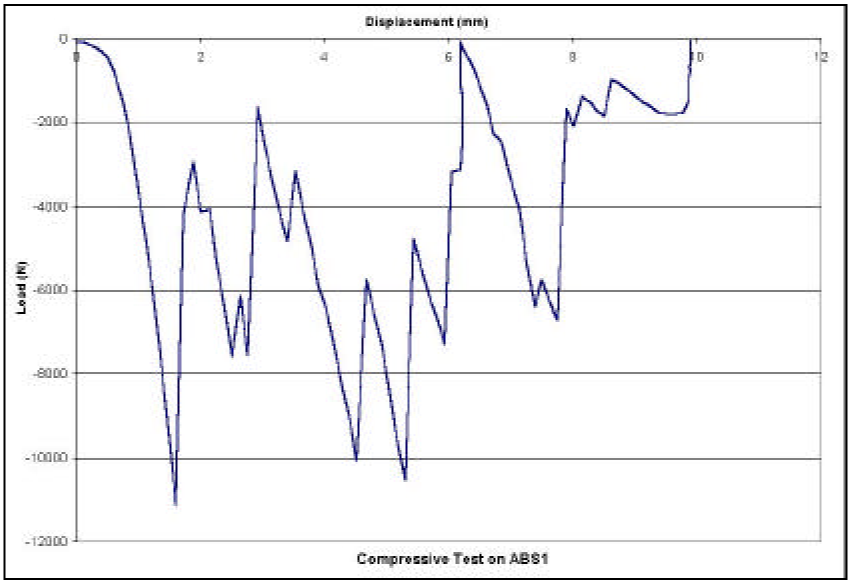
The calculated f-stat suggests that the density test differentiates between the two ice types. Thus, it is possible to simulate and characterize different types of ice in the laboratory, and the hypothesis for stage 1 has been proved correct.

5.3 Impact Tests

After 6 impact tests were performed, the instrumentation available was judged improper for this method of testing. In general, the indentation produced on the ice surface would not be more than 2 mm. It was observed, however, that thin specimens, in the order of 50 mm would commonly crack into two pieces instead of producing an indent.

5.4 Compressive Tests

In total 35 compressive tests were performed, of which 9 tests were on the chosen ABS1 and 10 on the chosen ABS2. The remaining tests were performed on the other prototypes of “bad ice”. Typical graphs of load against displacement for the compressive tests on ABS1 and ABS2 are shown in Figure 13.



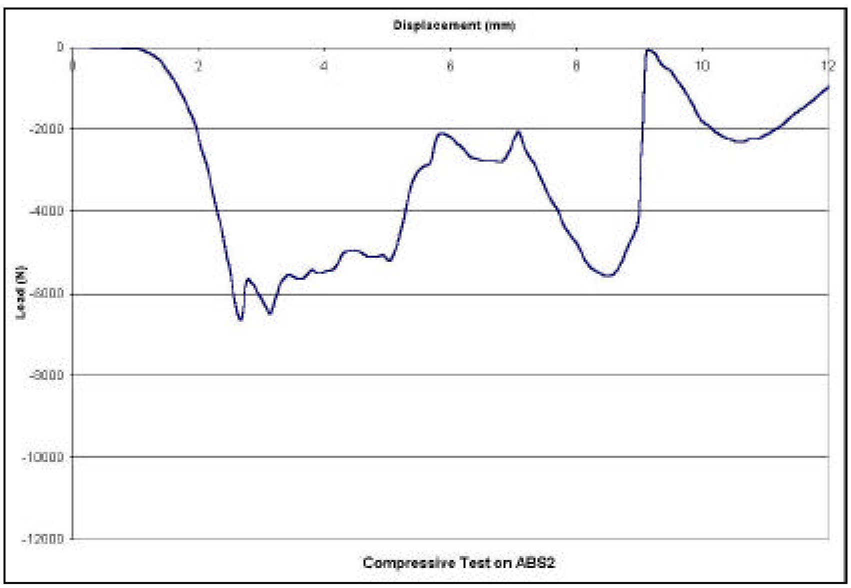


Figure 13: Typical graphs for compressive test on ABS1 and ABS2.

The value of compressive strength for each test was taken as the first peak in the graph. After the first peak the specimen would crack and shatter into smaller fragments, after which point the surface area was unknown. After data processing the following properties were attributed to each ice type:

Table 3: Mean values and standard deviations for compressive strength

Ice Type	Mean Compressive strength (N)	Standard Deviation (N)	Compressive Stress (MN/m²)
ABS1	9792	2837	0. 487
ABS2	8012	2749	0. 398

ABS1 and ABS2 have different mean compressive strengths. However, the standard deviations are large when compared with the mean compressive strength value, indicating a wide scatter in data. This was tested using an f-Stat Test function. This test indicated that there was only a 9% chance of ABS1 being different to ABS2. Judging by the data obtained and looking at the f-stat calculated, it is argued that the compressive test is of no quantitative statistical significance.

The test did however give some important qualitative observations about the behavior of each ice type. After the compressive test was performed on ABS1, the specimen stuck to the plates and fingers, whereas ABS2 would be wet to the touch. It is believed this is related to the mechanism and hence, the amount of energy absorbed by each ice specimen. Owing to its very brittle nature, ABS1 is not able to absorb much energy and hence, at the end of the experiment, is still very cold and able to stick to the plates. By comparison, ABS2 absorbed far more energy to the point where the surface was melting, following the experiment.

This observation and theory is corroborated by the graphs presented previously. The graph of ABS1 shows sharp peaks and very steep lines. For ABS2, the peaks are more rounded and the lines are less steep. The area underneath the curve can be considered to be proportional to the energy transferred to the specimen. On the graph the x-axis can be interchanged between time and displacement since the piston (arm) was displaced at a fixed rate. Hence, it is observable that ABS2 stored more energy before it failed in compression. Another indicator of this is the fact that ABS1 tended to fail much more explosively in a brittle fashion than ABS2.

The actual fracture load is highly dependent on initial crack distribution and other starting conditions. Owing to this fact, the force vs. displacement curves may characterize the ice better than the value of maximum load. To be able to compare the slopes of the curves, the faces of the specimens should have been evenly cut so the cross sectional areas were constant across samples and the same for the heights of the specimens. Unfortunately heights of the samples tested were not kept constant and were not measured in this project, so no further analysis on the graphs could be carried out.

6. Stage 2 – Results & Discussion

Stage 2 consisted of screwing ice screws into ABS1 and ABS2 specimens and recording the load at which the screws pulled out. In total, 36 pull tests were performed, of which 20 were on ABS1 and 16 on ABS2. A typical set of curves of force against displacement for the stage 2 testing is shown below.

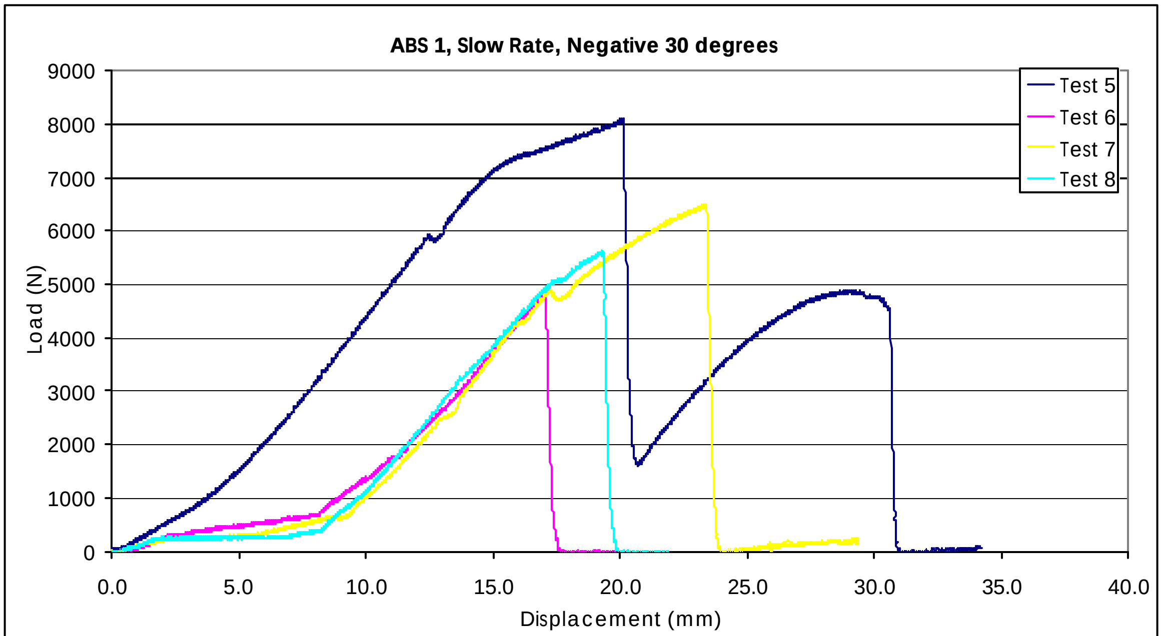


Figure 134: Typical set of curves for pull tests on ABS1.

The graph set in Figure 14 shows a steady ramp to the peak value where the screw/ice interface then breaks and the sustainable load drops to zero. The failure load of any test was taken to be the first peak in each graph. The data set labeled as 'Test 5' shows a second peak; this was where the ice screw became caught once again in the broken ice and then was able to again sustain a load before failing once more.

It was observed that the graphs for the faster loading rates were not as closely grouped as those for the corresponding slower rates. This again goes back to the point made in Section 5.4 that the faster, more brittle failures are more subject to the initial conditions of the ice. The faster test causes the ice to yield in the brittle manner whereas the slower rate test allows the ice to deform to a certain degree, and thus redistribute the stress and reduce the stress concentrations in certain areas. The results for all the tests can be found in Appendix B.

It should be noted that, since the sample size so was small (2-4 data points), the standard deviation of the sample does not necessarily give a reflection of the data. More tests need to be carried out to substantiate these findings. The major result from stage 2 is the following graph in Figure 14, which groups all the processed data obtained. This graph does not show the trends observed in the Harmston & Luebben study (Figure 16). Instead, it does not show any trend; rather it confirms that the optimum placement angle for screw placement is at zero degrees, i.e. perpendicular to the wall.

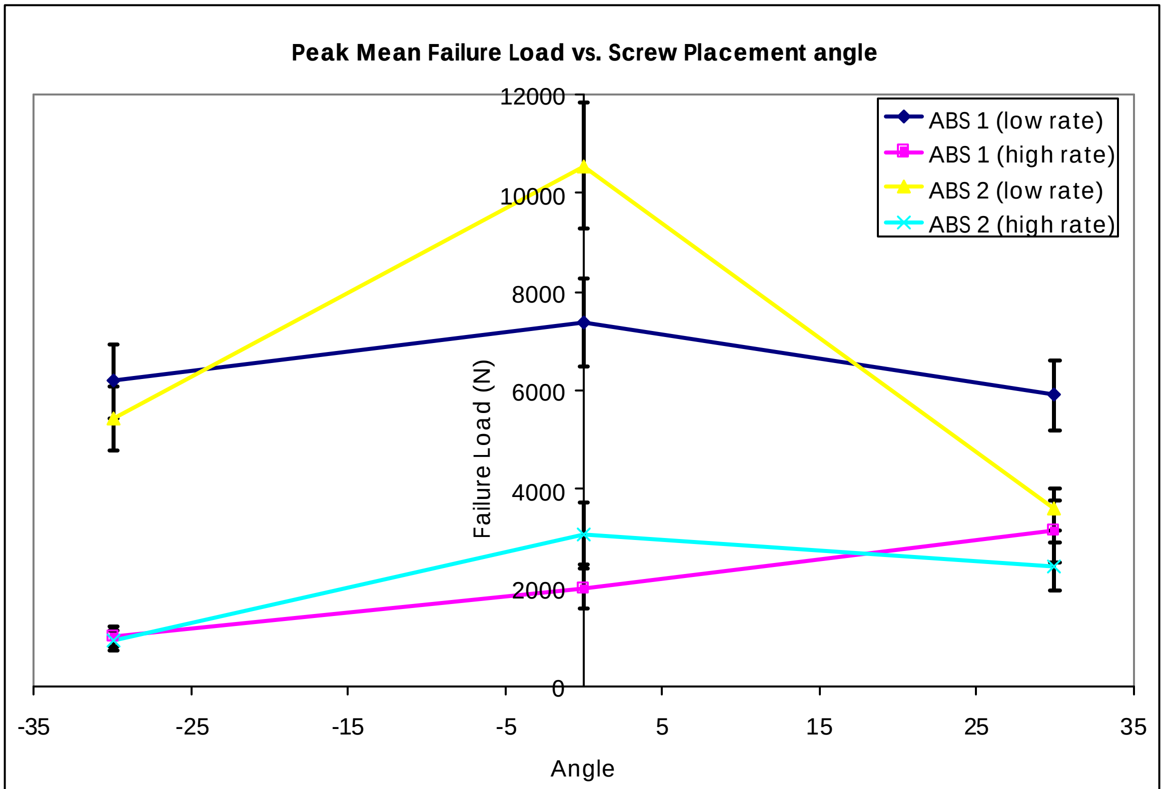


Figure 15: Graph showing Stage 2 data, failure load of the ice screw plotted against screw placement angle.

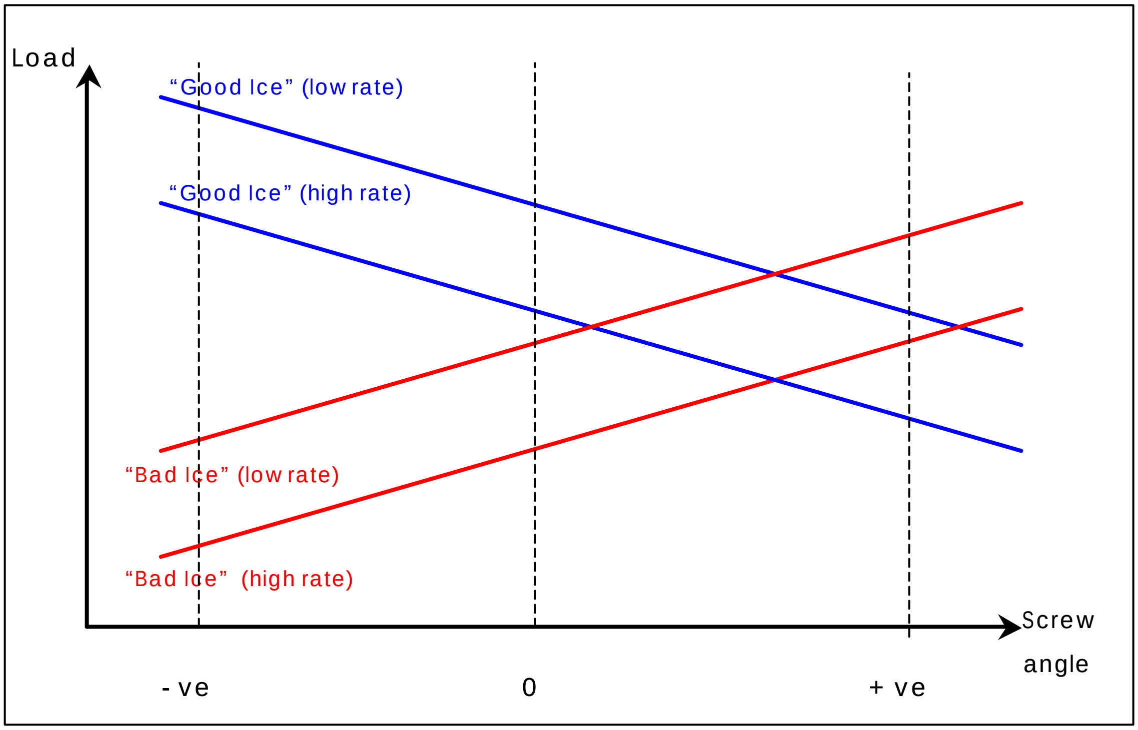


Figure 16: Graph showing the trends observed in the Harmston/Luebben study

Figure 15 does show a trend with the loading rates. It can be seen that the mean results for the lower loading rates give much higher failure loads than those using the higher loading rates. It is speculated that the reason for this observation is that at the slower loading rate the ice is allowed to deform and distribute the load more evenly throughout the screw/ice interface. At the higher loading rate however, the ice screw simply rips through the ice in a brittle fashion. The ice does not have time to adapt, and stress concentrations occur.

Figure 15 also shows the strongest screw/ice interface at the optimum screw placement angle is that of ABS2. The thousands of tiny bubbles within the ice act as a honeycomb structure. It is thought that the air pockets provide crumple zones and thus allow ABS2 to absorb more energy than ABS1, which has no such zones. One further explanation is that the bubbles act as crack blunters and prevent the crack from propagating.

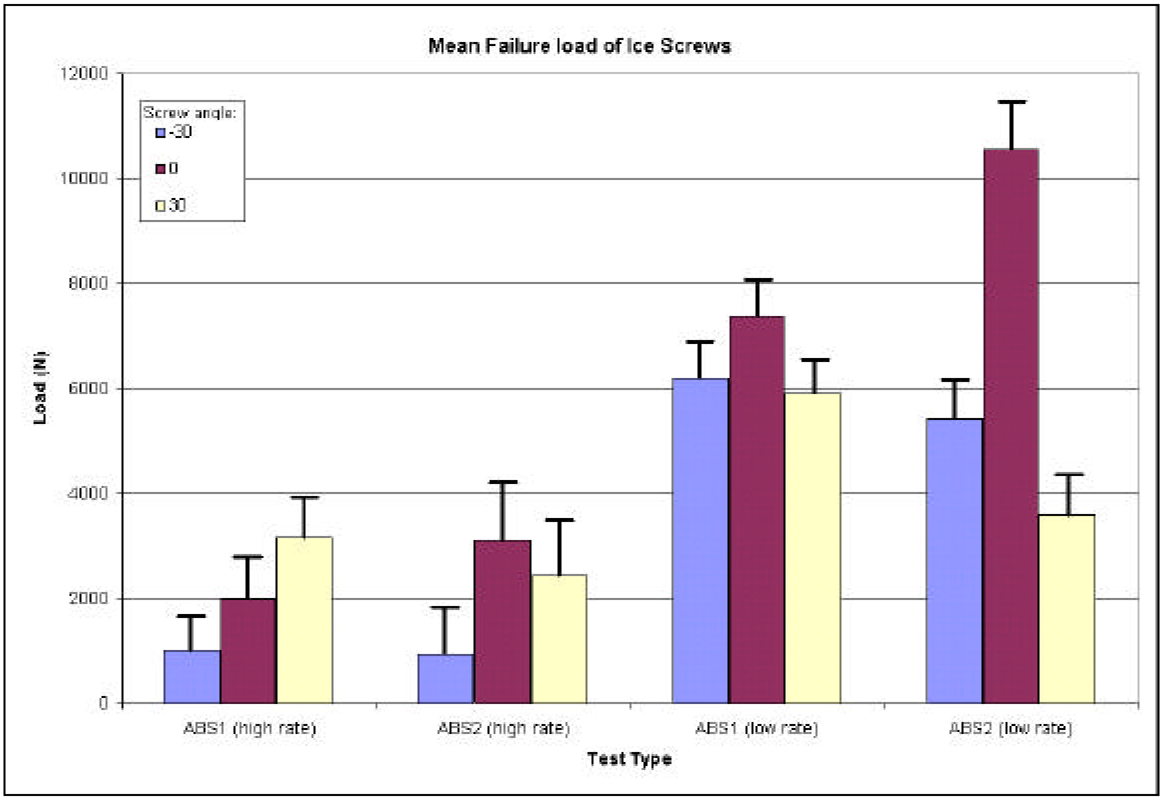


Figure 17: Mean failure load for ABS1 and ABS2 at high/low rate and all angles.

Figure 17 shows the range of failure data obtained for each different loading rate case. It is clear that, in almost all cases, the zero degree placement angle gives the highest pullout load. Also observable is that, for a low load rate case a negative angle is preferable to a positive angle, whereas for a high load rate case the positive angle holds more than the negative one. In the lower loading rate case the negative screw placement angle puts the load path in line with the pulling force from the MTS machine, thus allowing the screw threads to hold the load. In the higher loading rate case the positive angle of screw placement allows the ice screw to hold a higher load because the ice screw must then shear through 'extra' ice before it can be pulled out. The nature of the high rate pull out is that stress concentrations build up and break the ice in a brittle fashion, the positive screw placement angle puts more ice in the path of the failure crack than the negative angle.

7. Summary and Conclusion

7. 1 Major Findings

The density test used in stage 1 does provide an accurate way of characterizing ice. The compressive test, however, is not a valid test for measuring characteristics of ice because of the high dependency of initial conditions of the ice specimen. Nevertheless, the density test should not be used as the unique method for characterizing ice. It must be used in conjunction with another characteristic, because clearly it is possible for two different ice specimens to have the same density, and yet be significantly different.

Another finding, and possibly the most valuable to the climbing community, is the much greater dependency of loading rate on failure load rather than screw placement angle or ice type. This is significant to climbers as they have some control over the loading rate on an ice screw. Using a combination of ropes that can stretch more and friction devices in the belay system, the loading rate on an ice screw can be reduced significantly. This project has shown that a decrease in loading rate of a factor of 100 gives an increase in the supportable load of a factor of three.

7. 2 Suggestions For Future Work

As an extension to this project several areas of development have been suggested.

- Research on new methods for making a greater number of different ice types would lead eventually to the production of an ice type that mimics ice found in the environment to a higher level than the ones used in this project.
- Research must be carried out into the determination of other possible tests that can characterize ice effectively. This would allow the evaluation of the efficiency of the methods for producing repeatable ice types.
- Research to investigate the effects of screw length on failure load would be very useful to the climbing community.

8. Acknowledgements

This project would not have been possible without the valued help of the following people:

Our advisors, Dr Kim Blair and Dave Custer whose patient guidance and tremendous enthusiasm have been a constant source of inspiration.

Professor John Dempsey (Clarkson College) whose expert guidance on difficult issues has been invaluable.

Nemo Equipment Climbing Company whose expert insight into the sport of ice climbing has been instrumental in the development of the project.

And of course the 62X Faculty and staff with a special mention for John Kane, Dick Perdichizzi, Paul Bauer and Don Weiner whose experience in the sphere of project testing has proven essential.

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Appendix A – Recipe for Ice Formation

Forwarded message from John Dempsey

Date: Mon, 30 Sep 2002 10:35:05 –0400

From: John Dempsey

Subject: Re: Information on ice

To:

Stefano and Warren,

Please give my regards to Professor Parks. I'll give it a go. What size freezer do you have? Larger blocks will produce better results.

Suppose that you make up a cube of a box (quite well made so that it does not leak)- make it out of some softwood so that it absorbs water?? Cube of dimension N cm; suppose N is something like 25. Now insulate the bottom and all sides of the box; could just use that blue styrofoam but make the wall thickness of the order of 12 cm.

This is to stop any freezing nucleation on the sides or bottom. Now fill the box with cold water and put it in the freezer-prepare for leakage because the ice will try to expand outwards---which is why you want as much surrounding insulation as possible.

If you have the patience, monitor the temperature and stir that water so that it all cools more or less uniformly; right near freezing use some of the frost in the freezer as seed crystals and float the frost on top.

This method should give you repeatable clear blocks - the slower you grow the ice the better it will be in terms of say dislocation density etc.

Oh, almost forgot, you need a pressure release under the ice as it grows-like a pipe fitted to the side at the bottom-insulated or wrapped in heat tape, so that as the ice grows down, it will push water out the pipe-angle the pipe to maintain more or less the same pressure (head). In other words, let this excess water drip into a bucket or some such.

Be careful of thermal shock-let the ice warm up slowly. You can work at 0 Celsius or very near. I have observed with warm ice, that when you turn ice screws into it, you get these very fine radial crack under the expansion-interesting.

Temperature of the ice is probably your main variable. Let me know how this goes.
John Dempsey, Prof

Appendix B – Stage 2 pull-out test results.

Ice Type	'Load' Rate (inches/s)	Screw Angle (degrees)	Peak Value (N)				Mean (N)	Standard Deviation (N)
			Test 1	Test 2	Test 3	Test 4		
ABS1	0. 01	-30	4822	5559	6386	8021	6197	1374
ABS1	0. 01	0	6453	8306	-	-	7379	1310
ABS1	0. 01	30	4213	5262	6799	7355	5907	1435
ABS2	0. 01	-30	738	987	1164	1195	1021	210
ABS2	0. 01	0	1533	2431	-	-	1982	635
ABS2	0. 01	30	5559	2626	3920	489	3149	2141
ABS1	1. 0	-30	4764	7488	4022	-	5425	1825
ABS1	1. 0	0	10794	10319	-	-	10557	336
ABS1	1. 0	30	2911	4848	3044	-	3601	1082
ABS2	1. 0	-30	364	835	1622	-	941	635
ABS2	1. 0	0	3017	3177	-	-	3097	113
ABS2	1. 0	30	3702	2351	1244	-	2432	1231

Appendix C – Load Cell Specifications

Compressive Test:

Manufacturer: MTS Systems Corporation.

Model No.: 661.23A-02

Max load: 50 metric ton.

Linearity: ± 0.01% of Full Scale.

Pulling Test:

Manufacturer: Omega.

Model No.: LC101-10k

Max load: 10,000 lbs.

Linearity: ± 0.03% of Full Scale.

Hysterisis: ± 0.02% of Full Scale.

Repeatability: ± 0.01% of Full Scale.

Made from 17-4 Stainless Steel. This is extremely important since, if it were made out of another material, the water from the ice might have corroded it and hence changed its properties.

[1] Luebben, Craig, 'The Cold Truth – How Strong is Ice Protection?', Climbing Magazine, November 1997, pp. 106 - 115

[2] Harmston. C, 'Myths, Cautions and Techniques of Ice Screw Placement', Internal Report, Black Diamond Equipment, July 1998.

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