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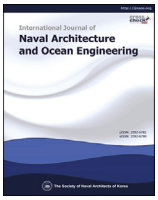

The effects of consolidation time on the strength and failure behavior of freshwater ice rubble

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ABSTRACT

Medium-scale tests were conducted to measure and observe the strength and failure behavior of freshwater ice rubble. A custom box measuring 3.05 m × 0.94 m × 0.94 m, with Plexiglas walls was built so that failure mechanisms could be observed. Ice rubble beams of nominal thickness 50 cm were produced by placing randomly sized ice pieces into the box filled with water at its freezing temperature. After the specified consolidation time, ranging between 0.2 and 70.5 h, the ice rubble beam was deformed by pushing a platen vertically downwards though the center of the beam until failure. For consolidation times less than 4 h, the ice beam failed progressively and tended to fail by shearing on macroscopic scale. At times greater than 4 h the beam failed by bending. The change in failure behaviour has been attributed to the degree of bonding between ice blocks.

1. Introduction

Ice ridges are large accumulations of ice rubble that form due to compression or shear in the ice cover. They consist of two parts, a sail and a keel. The keel is the submerged part of an ice ridge, which is often frozen at the top forming what is referred to as the consolidated or re-frozen layer. The non-submerged part of the ridge, the sail, is on average one fifth of the keel's depth (Timco et al., 2000). Ice ridges are complex features since they consist of individual ice blocks, random in size and orientation, and are bonded to each other with different degrees of strength from the consolidated layer to the base of the keel. Ridges are the thickest sea ice features in Arctic and sub-Arctic regions, and as such, must be considered during design loads estimation for vessels, offshore structures and subsea infrastructure.

A number of methods have been used to measure the mechanical properties of ice rubble. Initial tests began with the direct shear box test (Keinonen and Nyman, 1978; Prodanovic, 1979; Weiss et al., 1981; Hellmann, 1984; Fransson and Sandkvist, 1985). Timco and Cornett (1999) reviewed these data and suggested that the wide range of data corresponded to the characteristics of the shear box setup, which induces non-uniform deformation and stress distribution in the ice rubble and forces the sample to fail along an induced failure plane (which may not be the weakest one). Other methods to investigate the mechanics of ice rubble included the shear box tests by Urroz and Ettema (1987), triaxial shear test by Gale et al. (1987) and Wong et al. (1990), biaxial shear tests by Timco et al. (1992), Sayed et al. (1992), Løset and Sayed (1993), Cornett and Timco (1995), and in situ punch tests conducted by Leppäranta and Hakala (1992), Croasdale and Associates Ltd. (1997, 1998) and Heinonen and Määttänen (2000).

Azarnejad and Brown (2001) and Lemee and Brown (2002) conducted laboratory scale punch tests on freshwater rubble to investigate the failure processes under more controlled conditions than are possible in the field. Azarnejad and Brown (2001) examined the influence that beam thickness (0.2 m-0.5 m), consolidation time (0–3 h) and hydraulic ram speed (9–120 mm/s) have on shear strength. They found that with higher consolidation time the cohesion and friction increased due to the development of freeze bonds between ice blocks. They observed that the loading rate influenced both the failure mode and the peak load. At slow loading rates (<40 mm/s), a rectangular or trapezoidal plug of undisturbed ice rubble that spanned the entire thickness was pushed down by the platen and failure occurred mainly at the edges of the plug, while the surrounding rubble remained undisturbed. In comparison, at high deformation rates (45–120 mm/s) the failure occurred over a larger area both under the platen and in the surrounding ice

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Nomenclature

η	Porosity
τ	Shear strength
σ	Flexural strength
F_{peak}	Peak load at failure
F_B	Buoyancy force
F_{max}	Maximum net force
ρ_w	Density of water
g	Gravity
δ	Water level displacement
V_b	Nominal volume of submerged ice beam during deformation
V_s	Submerged volume of ice rubble beam before the test (after consolidation)
A	Projected failure area
S	The area of beam deformation at underside of the beam
w	Box width
L	Box length
h	Beam thickness
c	The distance from the edge of the platen to the support/friction bracket
m_{ice}	Mass of ice

rubble. In most cases a triangular or wedge shape was formed and did not span the entire thickness of the rubble beam. Lemee and Brown (2002) carried out similar tests using the same equipment but for larger ice rubble blocks and yielded comparable results. They suggested that ice rubble of larger dimensions failed at higher displacement. They also observed that the lower the initial temperature of the ice blocks, the more bonded the rubble.

In this paper, a series of medium-scale punch tests conducted in C-CORE's cold rooms are described. The focus of this work was to investigate the influence consolidation time had on the strength and failure behaviour of a 50 cm thick rubble beam. Tests consisted of deforming an ice rubble beam by pushing a platen vertically though its center until failure occurs (see Fig. 1). In each case two tests were conducted; the first on the undeformed rubble beam and, the second, on the deformed beam to investigate frictional properties between the ice rubble blocks. The load applied to the platen was measured using a load cell and hydraulic ram displacement with a string potentiometer. Video cameras were strategically positioned around the punch box to observe failure processes and air and water temperatures measured with Resistance Temperature Detectors (RTDs).

2. Apparatus and instrumentation

A custom-made box has been constructed for the test program that is 3.05 m in length and 0.94 m in width and height. The walls are made from Plexiglas (with a grid drawn on) so that failure mechanisms and ice block motions can be observed and tracked. The platen is rectangular and spans the entire width of the box so that failure mechanisms can be observed. A platen width of 0.4 m was chosen based on careful consideration of how it will influence the failure of the beam and the block dimensions. Load was applied to the platen using a 20,000 lb (9 ton) hydraulic ram. To help make beams of even geometry, a bottom plate, mounted on 4 threaded rods, was brought up to produced beams that were 50 cm in thickness (see Fig. 2).

During tests where the rubble was heavily bonded, the buoyancy of the non-loaded portion of the rubble was not sufficient to resist the applied load. As such, brackets had to be added to the end of the box to cause the beam to fail. This is similar to the procedure used by Azarnejad and Brown (2001) and Lemee and Brown (2002) where they glued small Plexiglas pieces on the tank walls to artificially increase friction between the tank walls and the ice rubble. The only difference being here that friction was only added to the ends of the box rather than the whole box to allow beams to fail in bending as well as shear.

A load cell was placed in line with the hydraulic ram to measure force applied to the rubble. A string pot was used to measure the vertical displacement and velocity throughout indentation. A total of six cameras were used to observe the tests from different views. Four were placed side-on to view the test through the Plexiglas window and two from the top (see Fig. 3). A high speed video camera (HSV) was used to view the mid-point of the beam where the failure planes occurred, which is needed for calculating the shear strength. Three LED work lights were mounted on the opposite side of the box to illuminate the ice rubble beam. Cameras were syncronized with the load and displacement data through a noise trigger.

Five (5) RTDs were used to measure air and water temperatures. Three (3) RTDs were placed in the water, two directly underneath the ice rubble beam (one at the centre of the box and the other at one end) and one at the bottom of the box (see Fig. 1). Two (2) RTDs were also placed in the air to measure cold room temperature at different locations. The RTDs' measurements were logged at a sample rate of 1 min, starting from the time that the box was filled

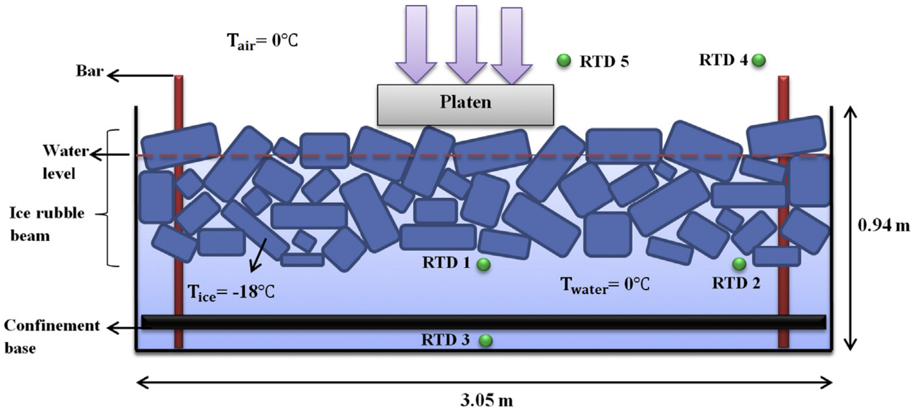

Fig. 1. Schematic showing the test setup.