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Strength–Temperature Equations for First-Year Ice, Second-Year Ice, and Two Categories of Multi-Year Ice

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Strength–temperature equations are presented for four categories of sea ice based on the borehole strengths (BHS) measured during 876 tests in 162 boreholes and their corresponding ice temperatures. The strength of every type of sea ice decreases with increasing ice temperature, as expected. The more novel aspect of the data provides equations to capture the strength–temperature relation, in addition to showing the temperature ranges where the strengths of each sea ice category overlap and where they do not. Equations based on ice temperature provide a reasonable prediction of the BHS for the different sea ice categories, but they cannot reproduce the measured strengths exactly. That is because temperature (proposed here as the most important and easily obtained variable) is but one of the factors that influence ice strength.

INTRODUCTION

Multi-year ice (MYI) and second-year ice (SYI) exert the highest loads on offshore structures (Frederking and Sudom, 2006; Sudom and Frederking, 2010). MYI and SYI are usually grouped together as "old ice," which the WMO (1985) defines as sea ice that has survived at least one summer's melt. The grouping is often necessary because it is challenging to differentiate the two types of old ice based on their surface appearance and sometimes their thickness (Johnston and Timco, 2008a, 2008b). Reliably distinguishing MYI from SYI and SYI from first-year ice (FYI) has become more pressing since the International Maritime Organization's (IMO) Polar Code came into effect in January 2017. Two of the three Polar Ship categories will be permitted to transit regions of FYI that may contain old ice inclusions if the ship has (a) an appropriate ice class and (b) an approved methodology for determining the ship's operational limitations in ice. One such methodology is POLARIS, which permits mariners to differentiate between SYI, "light" MYI, and "heavy" MYI when the ice thickness can be determined confidently (IMO, 2014; Transport Canada, 2019). That approach may seem reasonable, but gauging the severity of old ice by its thickness can be unreliable (B Gorman, personal communication, Jan 14, 2003; Johnston, 2012). The present study uses hundreds of strength and temperature measurements from four categories of sea ice to address the question "does classifying sea ice incorrectly have serious consequences for shipping and offshore activities?" The temporal aspect (i.e., time of year) is a very important consideration for ice strength because time is needed for different ice types and ice thicknesses to reach a given temperature. The seasonal aspect is not considered here, having been discussed elsewhere (Johnston, 2017).

The paper follows earlier publications wherein a larger suite of measurements (thickness, salinity, temperature, strength) was used to document seasonal property changes in FYI, SYI, and MYI (Johnston, 2006, 2014, 2017). Here, a subset of the data is used to document how ice strength changes with ice temperature and to provide equations for predicting the borehole strength (BHS) of the ice from known ice temperatures. The predicted BHS versus the measured BHS is compared for (i) individual test depths in the ice and (ii) the depth-averaged ice strength (bulk BHS). Relative errors in the predicted strengths are discussed.

METHODOLOGY

The sampling methodology will be summarized briefly, having been discussed elsewhere (see Johnston, 2014, 2017). Ice thickness was measured by using the drill-hole technique. The temperature, salinity, and strength of the ice were measured in up to five boreholes on each floe, most of which extended through the full ice thickness. Temperatures and salinities were measured on extracted ice cores (at a 20-cm depth interval), after which strength tests were conducted in that same borehole/core hole (at a 30-cm depth interval). A borehole indentor was used to measure the *in situ* confined compressive strength of the ice, or BHS. The borehole indentor is recognized as an accepted means of measuring the *in situ* ice strength (ISO, 2010), after its nearly five decades of use on sea ice in the Arctic and sub-Arctic. Measuring temperatures (at 20 cm) and strengths (at 30 cm) at different intervals necessitated interpolating temperatures for some strength tests from temperature measurements made above or below the test depth.

The present investigation focuses on the effect that ice temperature has on ice strength. Ice temperature is one of the easiest properties to measure in the field, and it can be reasonably estimated from known values of ice thickness, air temperature, and snow depth. In comparison, the ice salinity and ice density are more difficult to obtain/measure and therefore will not be discussed. The well-known effect that brine volume has on the flexural strength of FYI (Timco and O'Brien, 1994) and, by extension, the BHS of FYI (Timco and Johnston, 2002) has been documented previously. In comparison, brine volume has a lesser effect on the BHS of MYI because of its lower salinity (Johnston, 2014). The effect of brine volume on SYI strength has not been examined, to the author's knowledge.

ICE CATEGORIES

Floes were grouped into one of the four categories shown below, where accompanying information is given about the total number of floes sampled in that category. When classifying the

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KEY WORDS: Temperature, borehole strength, first-year ice, second-year ice, multi-year ice, sea ice.