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Estimation of the uniaxial compressive strength of Arctic sea ice during melt season

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ABSTRACT

A series of uniaxial compressive tests using ice cores collected in the Arctic Ocean was conducted in the cold laboratory on board R/V *Xuelong* during the summers of 2012 and 2014. A total of 130 ice samples were tested at temperatures ranging from −9 °C to −3 °C at strain rates ranging from $10^{-7}\,s^{-1}$ to $10^{-2}\,s^{-1}$ with the loading direction along the core axis. The uniaxial compressive strength of sea ice depends mainly on two parameters: sea ice porosity and strain rate during the test. Arctic sea ice presented characteristics of weak porosity effect and low transition strain rate. The effect of strain rate on the uniaxial compressive strength could be parameterized using a piecewise function for ductile, transition and brittle regimes. A power-law relationship was found between the uniaxial compressive strength of ice samples and their porosity. These relationships made it feasible to estimate the natural uniaxial compressive strength of ice as a function of *in-situ* porosity and strain rate. The results derived from the ice samples were extended to large-scale strength of ice sheets based on their porosity profiles determined using field measurements of ice physical properties. The strength of Arctic ice sheets in the summers of 2012 and 2014 was far less than previous estimates, probably because of accelerated interior ice melt caused by Arctic warming.

1. Introduction

The dramatic decay of Arctic sea ice, which in recent years has attracted much attention (Arrigo et al., 2008; Comiso, 2012; Day et al., 2012), has made the Arctic region more and more accessible (Khon and Mokhov, 2010; Liu and Kronbak, 2010; Shibata et al., 2013). However, sea ice is still the greatest challenge for Arctic shipping because of the large yearly variation in its spatial distribution (Lei et al., 2015). When ice interacts with the hull of a ship, it may rotate, collide with the ship or slide along the ship's hull (Kotras et al., 1984). The mechanical properties of sea ice are very important for maritime and other polar region operations in cold waters (Kjerstad et al., 2015; Montewka et al., 2015). Engineering properties of Arctic sea ice have been reported in previous studies, such as tensile strength (Kuehn et al., 1990), flexural strength (Saeki et al., 1981), failure envelope (Schulson et al., 2006), and uniaxial compression strength (Chen and Lee, 1988; Sinha, 1984, 1986). However, more information is still needed because of the rapid changes in Arctic ice conditions in recent years and the impending in production activities in the Arctic Ocean (Smith and Stephenson, 2013).

Uniaxial compressive strength, which is affected mainly by strain rate, is an important parameter when considering ice-structure interactions (Leisti et al., 2011). Sinha (1982) discussed the effect of strain rate under ductile failure and found a power-law relationship between strain rate and compressive strength. Arakawa and Maeno (1997) conducted compression tests over wide temperature ranges and found a similar relationship between the two parameters in both ductile and brittle strain-rate regimes. Schulson (2001) reviewed brittle compressive fracture and proposed a competing mechanism between crack-tip creep and crack propagation for the ductile-to-brittle transition regime.

Sea-ice porosity is another crucial factor affecting uniaxial compressive strength. Previous studies related sea-ice mechanics to brine volume (Johnston, 2006). However, for Arctic sea ice during melt season with ice temperatures higher than the phase transition point of brine, brine drains distinctly in the part above the waterline and most of the dried-up brine pockets are replaced by air, causing relatively higher air content and less strength. Therefore, it is more appropriate to use porosity, which is defined as the total volume of brine and air as a proportion of total ice, to characterize the mechanical properties of higher-temperature sea ice, rather than brine volume alone (Moslet, 2007). As the Arctic warms, a series of consequences for Arctic sea ice is

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caused, such as a longer melt period, a reduction of multi-year sea ice from a macroscopic viewpoint (Markus et al., 2009; Maslanik et al., 2011; Lei et al., 2016), and enhanced interior melting, which affects the physical properties of sea ice from a microcosmic viewpoint (Huang et al., 2016). Porosity can be determined from the temperature, salinity and density of sea ice (Cox and Weeks, 1983; Leppäranta and Manninen, 1988), which are physical indices reflecting the phase composition within sea ice. Hence, porosity is a comprehensive parameter to characterize the effect of the internal physical condition of sea ice on its mechanics.

However, most previous ice tests were conducted at small scale, and only a few studies examined the large-scale behaviour (Frederking and Timco, 1983; Chen and Lee, 1988). From an engineering perspective, the results of small-scale tests need to be scaled up to determine the large-scale strength of ice sheets. Based on small-scale strength tests, Timco and Frederking (1990) proposed a theory to estimate the uniaxial compressive strength at large scale using porosity and strain rate. They divided an ice sheet into nine layers from top to bottom and determined the porosity of each layer from its local average temperature, salinity, and density. The strength of all layers was then averaged to give the uniaxial compressive strength of the ice sheet. They then compared the calculated sea-ice strength with that measured in large-scale field tests and obtained excellent agreement between the two methods.

During the Chinese National Arctic Expedition in 2012 and 2014 (CHINARE-2012 and CHINARE-2014), *in-situ* measurements of ice physical properties were conducted in the Arctic basin, and the uniaxial compressive strength of ice samples was determined in an on-board cold laboratory. The motivation of this paper is to present the mechanical properties of Arctic summer sea ice under an environment of rapidly changing Arctic conditions. Because the data are potentially useful for Arctic navigation, a parameterization is needed that will relate the uniaxial compressive strength of Arctic sea ice to strain rate and porosity. This could be used to estimate the natural strength of sea ice from *in-situ* ice porosity. The intention is also to extend the results derived from small-scale tests to determine the large-scale strength of ice sheets according to the theory proposed by Timco and Frederking (1990). With these objectives, this paper consists of two main parts: field measurements of ice physical properties and laboratory tests of uniaxial compressive strength. Section 2 provides a description of the field measurements and mechanical tests. Section 3 presents the results for ice physical and mechanical properties. Section 4 gives measurement errors, comparative discussions, and an upscaling of the small-scale results. Finally, conclusions are drawn in Section 5.

2. Field measurements and laboratory tests

2.1. Field measurements

The study domain covered an area from 83.6°N–87.6°N to 123.1°E–161.7°E in 2012 and an area from 76.7°N–80.9°N to 151.1°W–157.6°W in 2014, where the ice concentration was more than 80% as shown in Fig. 1. A total of thirteen short-term ice camps and one long-term ice camp were completed during the two expeditions. The ice sheets where the ice camps were located were several kilometres in size. Vertical ice cores were extracted from the ice sheet at all ice camps for physical property measurements and mechanical tests. The specific conditions of the ice camps are listed in Table 1.

2.1.1. Measurements of ice temperature, salinity, and density

Vertical ice cores were retrieved from an ice sheet with a 9-cm-diameter ice auger. Once the ice core was extracted, ice temperature was measured immediately to avoid the effects of ambient air temperature. Holes were drilled at 10-cm intervals along the length of the ice core using a small electric drill. A temperature probe sensor with an accuracy of 0.1 °C was used. Ice salinity was measured using another ice core, which was cut into 10-cm-long segments from top to bottom with a handsaw immediately after extraction. These ice sections were then preserved in plastic bottles and taken back to the ship. A salimeter with an accuracy of 0.1 ppt was used to measure salinity after the ice sections melted. Ice density was determined using the mass-volume method. Ice cores were taken back to the on-board cold laboratory, and one of them was cut into 10-cm-long cylinders with a band saw from top to bottom. Each cylinder with a size of 9 cm × 10 cm was measured and weighed to determine the bulk density using a vernier caliper and a digital balance. These cylinders were then cut into two cubes 4 cm × 4 cm × 4 cm in size, which were measured and weighed again. The average density of the cylinder and the cubes was considered as the real density of each cylinder. The accuracy of the balance was 0.01 g. Because the summer sea ice could not be incised regularly, the accuracy of dimension measurement was about 0.1 cm, although the slide caliper had an original accuracy of 0.02 mm. The ice cylinders had a mass of 380–620 g, and the cube samples had a mass of 40–60 g; hence, the accuracy of the mass-volume method for ice density was approximately 40 kg m^{-3}.

2.1.2. Measurement of ice-crystal texture

The observations of ice-crystal texture were conducted in the cold laboratory with an ambient temperature of −15 °C. The ice core was cut into rectangular sections 5–10 cm in length and 1 cm in thickness from top to bottom with a band saw. These sections were then attached to glass sheets with a temperature slightly above 0 °C. The uniform thin water film produced between the ice sections and the glass sheets made them freeze together and without recrystallization. Once firmly attached, the ice sections were shaved to a thickness of less than 1 mm using a planer. These slices were then placed on a universal stage to observe the ice-crystal texture under crossed polarizing light. Ice-crystal texture was observed at all the camps except for 14-S5 because of an insufficient quantity of ice cores.

2.2. Uniaxial compression tests

2.2.1. Test devices

Ice cores were transported to the on-board laboratory to conduct uniaxial compression tests. For those ships that are not equipped with a cold laboratory, such as R/V *Xuelong*, the alternative is to prepare a mobile unit. The size of the on-board mobile cold laboratory was 6.1 m × 2.4 m × 2.6 m, and its lowest refrigeration temperature was −30 °C. A thermotank was used to preserve ice samples at the required temperature.

Fig. 2 shows the uniaxial compression test equipment. The uniaxial compression device was powered by a hydraulic pump. A force sensor with a capacity of 50 kN and an accuracy of 25 N was attached between the steel compression axle and the compression plate to record the load-time history. A laser displacement sensor with a measuring range of 2.5 cm and a linearity of 0.05% full-scale range was attached to the columns of the compression device, and an aluminium plate was fixed onto the axle of the compression plate to reflect the laser from the sensor. These components were used together to record the displacement-time history of the compression plate. The force sensor and the laser displacement sensor recorded synchronously when the compression machine began to operate. A frequency converter was used to control the loading rate.

2.2.2. Sample preparation

All the ice samples were stored in the cold laboratory at −15 °C. According to Schwarz et al. (1981), the suggested dimensions of a uniform standard uniaxial compressive specimen are 7 cm in diameter and 17.5 cm in length. After measurements of ice density and crystal texture, the remaining ice cores were cut into rough-cut cylinders with a length of 20 cm using a band saw. To ensure roundness and straightness, the diameter of the rough-cut samples was cut from 9 cm