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Increasing the flexural strength of columnar-grained ice by an icy coating

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Abstract

New experiments have revealed that a thin layer of granular ice bonded to salty and to salt-free columnar-grained ice increases flexural strength when the composite material is rapidly bent to the point of failure through brittle fracture. When bent slowly within the regime of ductile behavior, the layer has no detectable effect. Strengthening is attributed to the suppression of cracking; its absence, to dislocation creep.

1. Introduction

When formed under natural conditions, floating ice covers on lakes, rivers and cold oceans are often covered with snow. When wetted and allowed to cool, the snow can consolidate by freezing, forming a coating of an icy granular layer bonded to underlying columnar-grained material. On Arctic and Antarctic Sea ice, for instance, the average snow thickness is of the order of 10 cm (Weeks, 2010), implying potential icy layers of around 10% of the thickness of the covers.

The question arises: does an icy coating significantly affect the flexural strength of ice? Over the years, the flexural strength of ice has been studied a number of times (e.g. by Gow, 1977; Timco and Frederking, 1982, 1983; Parsons and others, 1992; Timco and O'Brien, 1994; Kovacs, 1997; Timco and Weeks, 2010; Aly and others, 2019; Wang and others, 2022). To our knowledge, this question has not been explored.

To seek an answer and to fill a gap in one's understanding of ice mechanics, we performed new experiments in the laboratory on both salty and salt-free columnar-grained ice. As will become apparent, we found that when the ice is bent slowly to allow creep deformation, a thin coating has no detectable effect. On the other hand, when bent rapidly to the point of brittle fracture a coating/layer as thin as 6% of the underlying ice can increase flexural strength by as much as 37%.

2. Experimental procedure

We performed the experiments in the laboratory on columnar-grained ice of three kinds atop which a coating or layer of freshwater granular ice had been bonded: first-year sea ice harvested from the winter cover on the Beaufort Sea, saline ice produced in Dartmouth's Ice Research Laboratory (IRL) following a standard procedure (Murdza and others, 2021), and freshwater ice also produced in the IRL following the same procedure. These are the same kinds of ice whose across-column flexural strength was measured and discussed earlier (Iliescu and others, 2017; Murdza and others, 2020, 2021, 2022a, 2022b, 2023).

Each columnar-grained aggregate possessed the S2 growth texture (Langway, 1958), Fig. 1a-g. The densities of freshwater, saline, and sea ice were 914 ± 2, 878 ± 11 and 906 ± 4 kg/m^3, respectively. The salinity of meltwater from both saline and sea ice was 3.0 ± 0.9 and 3.0 ± 0.3 ppt, respectively. The average column diameters for freshwater, saline and sea ice were 5.5 ± 1.3 mm, 3.8 ± 0.9 mm and 2.7 ± 0.4 mm, respectively.

From each type of ice beams were milled of dimensions 300 mm in length × 86 mm in width × 16 mm in thickness (Fig. 1j). The long axes of the columnar-shaped grains were oriented perpendicular to the largest surface, as in nature. Placed atop the plates, cooled to −10°C, was a thin (1 ± 0.1 mm) layer of freshwater ice fragments (of diameter 0.25–1 mm) that had been obtained through blending and sieving (Fig. 2a). The fragments were sprayed with freshwater (∼10 ml) cooled to about 2°C, saturated, and then allowed to consolidate through freezing for 24 h (Fig. 2b). In that way, granular-columnar composites were produced in which the granular layer comprised of grains of average diameter 0.34 ± 0.06 mm, comparable in size to some polar snow crystals in Kikuchi and others (2013). The layer constituted 1/17 or ∼6% of the total thickness of the beam. Figure 1h shows an example of the composite microstructure.

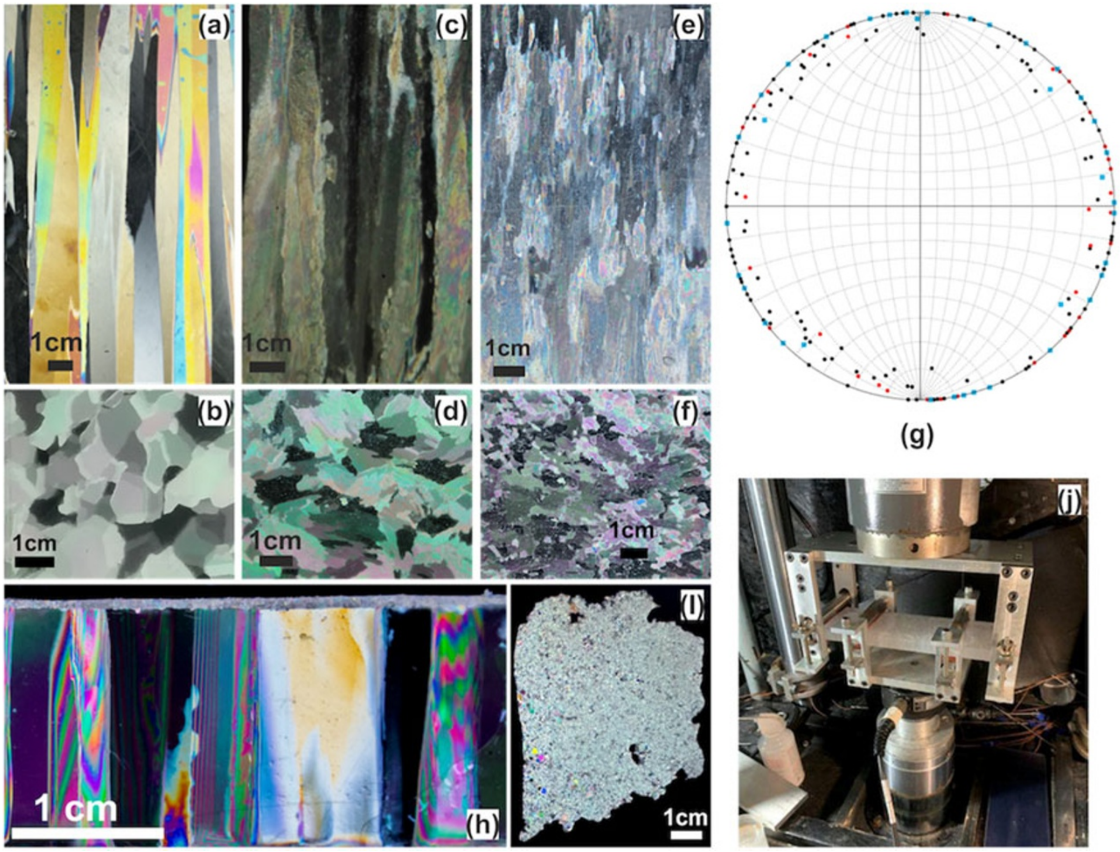

Figure 1. Photomicrographs of ice microstructure: vertical (a) and horizontal (b) thin sections of freshwater ice; vertical (c) and horizontal (d) thin sections of saline ice; vertical (e) and horizontal (f) thin sections of sea ice. (g) Stereographic projection plot of crystal c-axis orientations for freshwater (black), saline (red) and sea ice (blue). (h) Microstructure of composite freshwater ice in a vertical section: the thin granular layer (i) is on the upper surface, and the S2 columnar grains are oriented vertically. (j) Photograph of the four-point bending apparatus with a saline ice sample placed, connected to an MTS hydraulic testing system.

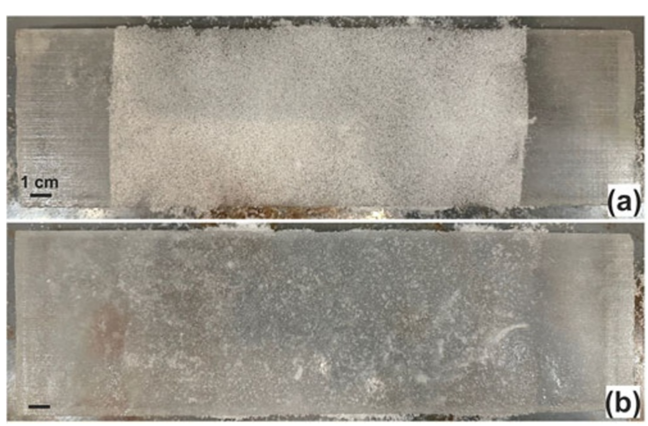

Figure 2. Photographs of a freshwater ice plate with a thin layer of freshwater ice fragments placed atop: (a) before spraying, and (b) after spraying with freshwater and consolidating the fragments through freezing.

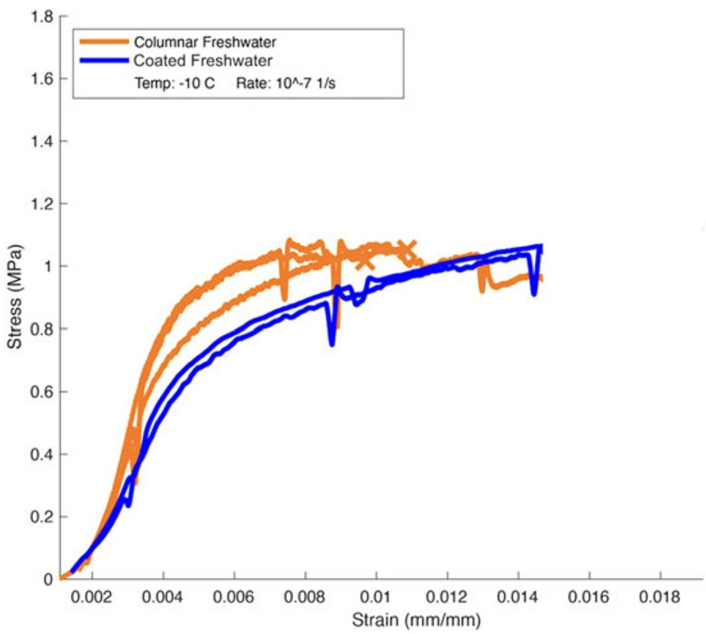

Figure 3. Stress–strain curves for freshwater columnar ice and composite ice loaded slowly at a constant outer-fiber strain rate of 10^{-7} s^{-1}. Note that the sudden drops and subsequent recoveries in the stress curves are not due to sample behavior (such as crack formation), but a result of machine recording malfunction.

The beams were bent in a 4-point flexural manner (Fig. 1j) according to ASTM Standard C1341-123, Test Geometry IIA, using the same bending system employed and described by (Murdza and others, 2021). The outer-fiber stress, $\sigma$and strain, ε, were computed from the relationships:

$$\sigma = \frac{3PL}{4wh^2}, \tag{1}$$

and

$$\varepsilon = \frac{8hD_y}{L^2}, \tag{2}$$

where P denotes the applied load, D_y is the displacement at the load points (i.e., the displacement of the actuator) and L, w and h, respectively, the beam length, width and thickness. Care was taken to ensure that the granular layer was stressed in tension. With respect to its structure, the columnar ice was loaded in a direction parapedicular to the long axis of the grains, as in a natural ice cover. In the interests of reproducibility, measurements were made a number of times under each set of conditions. All measurements, 40 in total, were made in a cold room at −10°C

To explore both the ductile and the brittle regimes of inelastic behavior, some beams were bent slowly at an outer-fiber strain rate of 10^{-7} s^{-1}; others were bent rapidly at an outer-fiber strain rate of 10^{-4} s^{-1}. Tests at the lower rate were performed on freshwater ice only, owing to a limitation on the availability of the salty ice.

3. Results

When bent slowly (at 10^{-7} s^{-1}) the ice behaved in a ductile manner (Fig. 3). The outer-fiber stress initially increased with increasing strain and then tended to level off. The tests were terminated after ∼36 h at which point an outer-fiber strain of about 0.013 had been imparted. At that strain the outer-fiber tensile stress on the coating-free ice reached the level of 1.10 ± 0.01 MPa. In comparison, the outer-fiber stress on the coated ice at the same strain reached the level of 1.11 ± 0.04 MPa. In other words, the finely grained icy layer had no detectable effect on the ductile flexural strength of the freshwater ice.

When bent rapidly (at 10^{-4} s^{-1}), on the other hand, the three ices fractured in a brittle manner: the stress increased with increasing strain in a pseudo-linear manner and then dropped suddenly as the beam broke into two pieces. Under this condition, the coating had a significant effect. The strength of the freshwater ice increased by 37%, from 1.67 ± 0.22 to 2.29 ± 0.20 MPa. Similarly, the strength the saline ice increased by 18%, from 0.96 ± 0.13 to 1.13 ± 0.18 MPa and the strength of the sea ice increased by 16%, from 1.40 ± 0.07 to 1.63 ± 0.13 MPa. Figure 4 summarizes the measurements. The salty ices are weaker than the freshwater ice owing to the stress-concentrating effect of brine pockets within their microstructures. The sea ice was stronger than the saline ice because its grain size was smaller and its density was higher.

Our measurements on coating-free ice that exhibited brittle behavior compare favorably with earlier measurements. For example, Timco and O'Brien (1994) reported a flexural strength of 1.73 ± 0.25 MPa for freshwater ice at temperatures below −4.5 °C. Additionally, their Figure 7 shows that the flexural strength of salty ice with salinities similar to ours ranges from approximately 0.3 to 1.6 MPa. The flexural strength of our saline and sea ice also falls within the range of ∼0.6 to ∼1.4 MPa reported by Timco and Frederking (1983) for the flexural strength of mid-winter natural sea ice. Furthermore, when our flexural strength values are converted to tensile strength by dividing by 1.7, as suggested by Ashby and Jones (2012), our results align well with the tensile strength of both freshwater ice and sea ice reported by Carter (1971) and by Richter-Menge and Jones (1993).

4. Discussion

The absence of strengthening under conditions leading to ductile behavior is consistent with current understanding of the underlying deformation mechanisms. Accordingly, when polycrystalline ice of 0.34 mm grain size is slowly deformed at a strain rate of 10-^{7} s^{-1} at a high homologous temperature—where −10°C corresponds

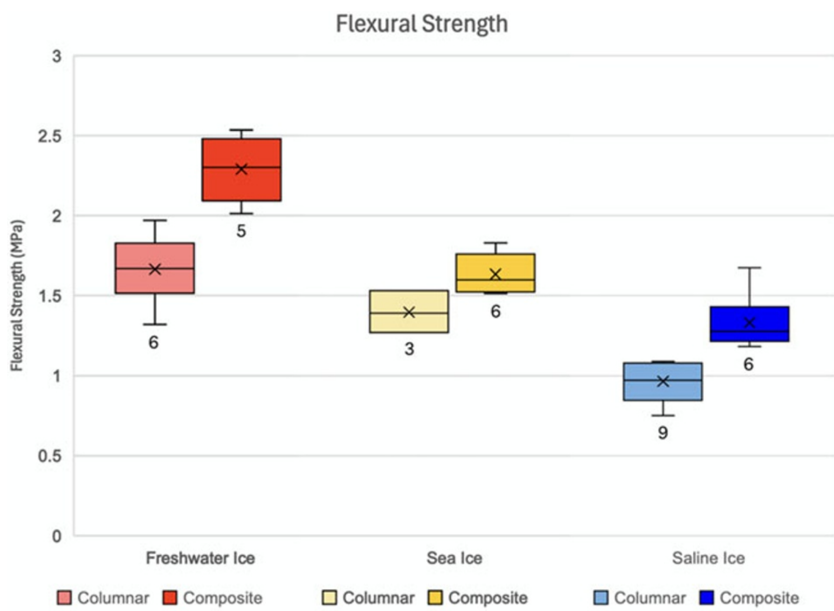

Figure 4. Box plot of flexural strength for columnar and coated ice in freshwater, sea ice and saline ice categories loaded rapidly at a constant strain rate of 10^{-4} s^{-1} (sample sizes are indicated under each box). In each group, the lower box with the lighter color corresponds to columnar ice, and the upper box with the darker color corresponds to coated ice.

to $T_h = 263/273 = 0.96$—inelastic deformation is dominated by dislocation creep (Frost and Ashby, 1982). Theory dictates that mechanism is independent of grain size, in keeping with the experimental observations (Duval and others, 1980; Jacka, 1984, 1994). For that reason, the thin, granular layer had no detectable effect on the flexural strength of the composite when slowly bent, at least of the all-freshwater composite.

When rapidly bent and brittle failure ensued, the surface layer increased strength. The layer, we hypothesize, suppressed crack formation. The tensile strength of freshwater granular ice scales as the reciprocal of the square root of grain size and for ice of 0.34 mm grain is expected (from Equations 10.1 and 10.2 of Schulson and Duval, 2009) to be around 2.2 to 2.8 MPa. These strengths are comparable to the outer-fiber tensile stress at fracture of 2.29 ± 0.20 MPa of the coated freshwater ice. Why the coating is less effective in strengthening the rapidly bent salty ice (16 and 18% vs 37%) is not clear. Perhaps the salt interacted with the coating and weakened it, and more work is needed.

More work, too, is needed to determine whether the effect measured in the laboratory, relatively large though it is, is detectable in the field. There icy coatings on floating ice covers, subjected to rapid flexing under the action of waves, may be less regular than in the laboratory. What is now known from the experiments described in this letter, however, is that the potential exists for a significant effect.

Data availability statement. The data supporting the findings of this study are publicly available at the Arctic Data Center repository (Murdza and others, 2024).

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Competing interests. The authors declare that they have no competing interests.

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