Response to the Comments of Reviewer1

This paper presents mechanical property test results of Antarctic sea ice and links those to the prevailing physical properties including porosity, brine volume, grain size, platelet spacing and strain rate. The paper contributes to the state of the art by providing valuable insights of the applicability of several existing methods to the estimation of Antarctic sea ice properties, specifically in the Prydz Bay, and by offering location-specific ice mechanical property and bearing capacity estimation for engineering purposes. The extensive effort to accomplish the research purpose is appreciated and the results are presented and analysed in a logical and clear manner.

We appreciate warmly for the reviewer's earnest work. The comments are constructive, and we have revised the manuscript accordingly. Detailed answers to all comments are provided below.

The specific comments are:

Comment: The brine volume and porosity were calculated using ice temperature, salinity and density using Cox and Weeks formulae. The calculation will most likely involve uncertainties which may have an impact on the later investigations. The authors are suggested to comment on the significance of this uncertainty source and its influence on the results of this work.

Response: Thanks. We will stress this issue in the revised manuscript. Since it is not easy to quantify the uncertainties (the error propagation estimation needs independent direct measured variables, see respond below), so we talk about it in a qualitative way as below.

It is noteworthy that the calculation most likely involves uncertainties introduced by the measurement errors of ice physical properties, especially for sea ice porosity, of which the air volume fraction is largely dependent on ice density (Timco and Frederking, 1996).

Comment: Line 105: the authors are suggested to specify the speed of loading. It is not very clear what 'time-of-loading' means. I assume the ice beam fails very soon after loaded.

Response: We will use strain rate to define loading speed in the new version. The strain rate in three-point bending test is calculated using equation below (see Han et al. (2016))

$$\dot{\varepsilon}_{\mathrm{f}}=\frac{6h\dot{\delta}}{l^2}$$

where $\dot{\varepsilon}_{\mathrm{f}}$ is strain rate of bending test; $\dot{\delta}$ is displacement rate of the pressing plate; l is span between supports; h is height of the beam. Result shows that the strain rate of our bending tests varies from 10^{-5} to 10^{-3} s^{-1}.

Comment: Line 199-200: some example references can be added to explain 'other commonly used functions'

Response: The reported relationships between sea ice flexural strength and square root of brine volume fraction were in exponential (Timco and O'Brien, 1994) and linear froms (Krupina and Kubyshkin, 2007). In this paper, we adopted more expressions including exponential, linear, logarithm and power functions. We will list these mathematical functions we used as we think it may be much clear than showing the references.

Comment: The confidence intervals adopted for various analyse vary from 90% (e.g. Figure 7) to 99% (Figure 6). Is there a ration behind the selection of confidence intervals?

Response: The confidence intervals are determined according to the individual significance levels (p) obtained by regression analyses. For example, in Fig. 6, p of the best-fit relationship between flexural strength and square root of porosity was less than 0.01, so we chose 99% as the confidence interval. In Fig. 7, $p > 0.1$ for the flexural strength-grain size best-fit equation, so the confidence interval was selected as 90%; and $p < 0.05$ for the flexural strength-platelet spacing best-fit equation, so the confidence interval was selected as 95%. Moreover, for the best-fit equations with various significant levels in different regimes, such as in Fig. 10a, we chose the maximum value as the final confidence interval for all the best-fit lines.

Comment: It would be helpful to indicate the range of salinity measured among the samples. It is found that the flexural strength is not sensitive to brine volume. Would it be possible that this is because of the small range of salinity coverd by the samples (since they are from the same ice block)?

Response: Yes, what the reviewer suggested could be a reason. The salinity of congelation-ice samples in the bending tests was 1.0–5.1 psu. The brine volume fraction is a function of ice temperature, salinity, and density, and the square root of brine volume fraction of our samples was 0.11–0.27. The range is narrower than that reported in Timco and O'Brien (1994) (0–0.5) and in Karulina et al. (2019) (0.16–0.39), which probably makes that the flexural strength of our samples is not sensitive to brine volume. We will also add the above discussion in the revised manuscript.

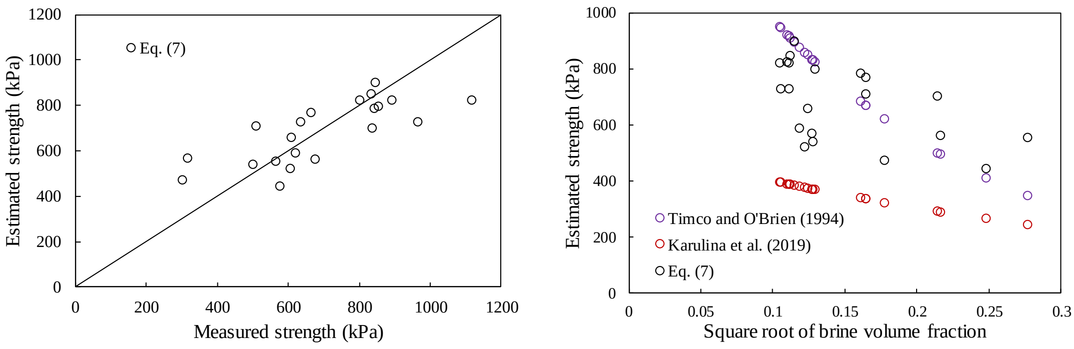
Comment: How does Eq. (7) compare to the existing equations in the literature? Are they similar or do they differ a lot?

Response:

(1) First, as shown in the Figure (a) below, the flexural strength estimated using Eq. (7) agrees well with the measured strength with correlation coefficient of 0.75 ($p < 0.01$).

(2) Second, to better compare our best-fit equation (Eq. 7) with existing equations reported in Karulina et al. (2019) and Timco and O'Brien (1994), the results of flexural strength calculated based on our test data were plotted against the square root of brine volume fraction in Figure (b). Results showed that the strength estimated using Karulina et al. (2019) was much lower than that estimated using ours. The strength estimated using Timco and O'Brien (1994) agreed better with that estimated using ours than Karulina et al. (2019) and only overestimated by 1.1 times.

The above comparisons will be added in the revised manuscript.



(a) (b)

Figure Comparisons of estimated strength using our best-fit equation with (a) measured strength and (b) estimated strength using existing equations in the literature.

Comment: Line 258-259: the sample size may be too small to draw the conclusion on temperature effect.

Response: The statement about the effect of ice temperature on snow-ice effective modulus will be deleted.

Comment: The first paragraph of 3.4.1: nice and thorough explanations are provided here to explain the measured trend of compressive strengths. More references are suggested here to support the reasoning, so that it does not look like own speculation. Same for later parts with such explanations.

Response: Thanks. More references of Gold (1997), Ji et al. (2020), Kuehn and Schulson (1994), Sinha (1988), and Schulson (2001) will be cited to support the relative statements in this section.

Comment: The small size ice samples are cut from different positions along the thickness direction. Does the measured mechanical properties exhibit dependence on the thickness position? Typically congelation columnar ice is stronger at the top than at the bottom. This relates to Figure 14, where all the measurement has been plotted together in the same figure. The lower evelope probably corresponds mainly to flexural strength at the bottom, while in the case of bearing capacity ice fails at the top layer. This leads to conservative estimation of the bearing capacity.

Response:

(1) Due to the limited number of samples under each ice temperature and the focus of examining the effects of porosity and brine volume on sea ice strength, we did not record the thickness position of our bending samples in the whole ice sheet. Therefore, the dependence of strength on the ice depth is not able to be checked here. In general, as the reviewer said, the ice is stronger at the top than at the bottom.

(2) For estimating the bearing capacity of landfast sea ice, as the reviewer said, we conducted a conservative estimation. Because the real scenario is that the cargos are unloaded on the ice sheet, and thus, the strength of ice sheet is needed rather than that of small-scale samples. While the elastic modulus of sea ice varied along ice thickness, making it difficult to obtain the real distribution of stress along ice thickness. So, we conducted a conservative method for safe designing in this paper by adopting the minimum flexural strength. All the measured strength of ice samples was plotted in Fig. 14a, and the lower envelope of flexural strength was selected to represent the strength of ice sheet. The results indicate a minimum load that can put on ice.

    In addition, we think that the above assumption is close to the actual scenario to some degree. As the load is applied on ice sheet, the sheet should be compressed at the top and tensioned at the bottom. Ice is a material which is strong in compression and weak in tension. So, the ice sheet deflects until the first crack or yielding develops in the underside of the sheet beneath the center of the load (Masterson, 2009). The low strength often occurs at the bottom of ice sheet because of the higher ice temperature near freezing point; therefore, it is reasonable to use the lower envelope of flexural strength.

The above discussion will be added in the revised manuscript.

Comment: It may be worth also mentioning the influence of platelet spacing in the conclusion part.

Response: Thanks. The statement below will be added in *Section Conclusions*:

The effects of sea ice sub-structure on columnar ice strength were investigated. Both flexural strength and effective elastic modulus increase with increasing platelet spacing, while the influence of grain size is not significant.

Some technical corrections:

Comment: Line 51: the statement after 'because' tells why there are more understanding of mechanical properties of Arctic sea ice, but not really the reason why there are very few for the Antarctic. Consider rephrasing to make it more natural.

Response: The statement will be rephrased as below:

The mechanical properties of Arctic sea ice have been widely investigated in the last century because of booming oil and gas exploration in the Northern Hemisphere polar regions. While the understanding of mechanical properties of Antarctic sea ice is limited due to less human and industry activities than those developed in the Arctic.

Comment: Line 53: 'south pole' means exactly the pole (latitude 90). Here it should be something like 'Antarctic continent'.

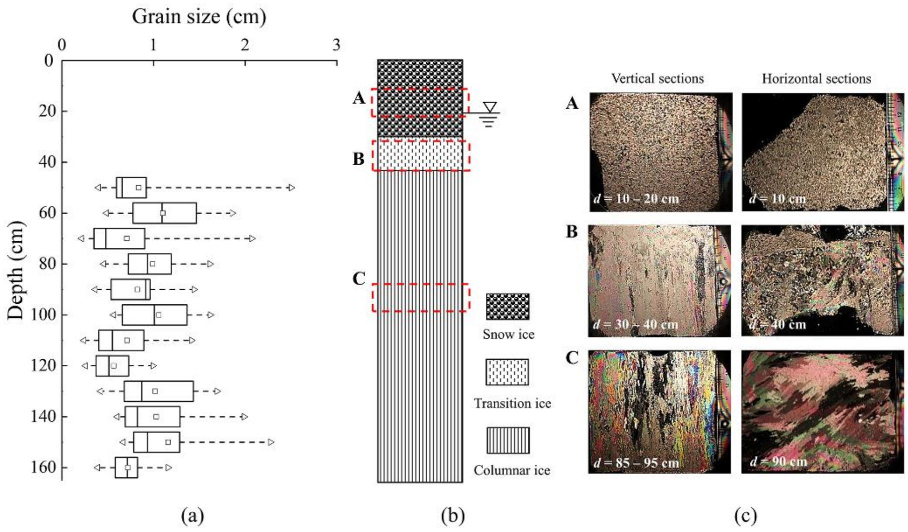
Response: It will be replaced with Antarctic regions.

Comment: Line 128: rule -> ruler?

Response: Yes, it is ruler. Corrected accordingly.

Comment: Figure 4b: the pictures are small, making it difficult to see clearly the crystal structures. Consider enlarging.

Response: A much clearer figure will be exhibited as below.



Comment: Eq. (8): typically equation follows immediately where it is firstly mentioned -> move 'overestimation ...' to after Eq. (8)

Response: Corrected accordingly.

Comment: Line 379: empirical -> empirically

Response: Corrected accordingly.

Comment: Line 420: photted -> photoed

Response: Corrected accordingly.

Comment: Line 438: radiuses -> radii

Response: Corrected accordingly.

Reference

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Ji, S., Chen, X., and Wang, A.: Influence of the loading direction on the uniaxial compressive strength of sea ice based on field measurements, Ann. Glaciol., 61, 86–96, https://doi.org/10.1017/aog.2020.14, 2020.

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Timco, G. W. and O'Brien, S.: Flexural strength equation for sea ice, Cold Reg. Sci. Technol., 22, 285–298, https://doi.org/10.1016/0165-232X(94)90006-X, 1994.