Proceedings of the 25th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2019, Delft, The Netherlands

Experimental study on the tensile strength of granular sea ice based on Brazilian tests

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ABSTRACT

The tensile strength is a fundamental mechanical property of sea ice and is a key parameter for the designing of structures in ice infected waters. To study the tensile strength, the Brazilian tests were carried out on the granular structure ice in the Bohai Sea. Under concentrated loads, the discs are assumed to carry and later to be failed from strong tension stresses. The tests were performed on the ice samples with various thicknesses, temperatures and loading speeds. The ice texture, salinity and density were also measured. In all the experiments the ice samples were failed in splitting manner. The results show that the tensile strength has weak dependency on the loading speed and sample thickness. On the other hand, the tensile strength increased from 0.44MPa to 1.4MPa with total porosity decreased from 75‰ to 10‰. Compared with previous tests based on uniaxial tension tests, the results have a similar trend. However, the values of granular ice are between that of horizontal orientated and vertical orientated columnar ice. It means that under tension granular ice is stronger than columnar ice in horizontal orientation but weaker than that in vertical orientation. This study has identified that the Brazilian tests provide expected ice failure pattern and desirable results. It could be an efficient alternative for tensile strength measurement.

KEY WORDS: Granular sea ice; Tensile strength; Brazilian tests; Porosity; Experiment.

1. INTRODUCTION

The tensile strength is a fundamental mechanical property of sea ice. It is defined as the maximum stress that the ice can carry before failure (Timco and Weeks, 2010). To determine the tensile strength, ice need to be carefully machined to a dumbbell shape and tacked to metal cups by refreezing, so that the fracture may occur in the middle of the sample instead of the ice-platen conjunction (Cole et al., 1985; Lee, 1986; Richter-Menge et al., 1993). However, the direct methods (uniaxial tension) take significant time and efforts on the sample preparation

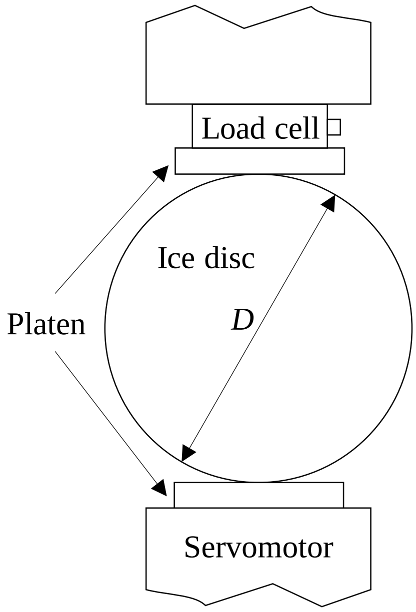
(Mohamed and Farzaneh, 2011). These time-consuming procedures make it inefficient and unpractical to be carried out in the field.

As alternatives, some indirect methods are applied to measure the tensile strength of geomaterials, such as simple beam tests, cantilever beam tests, ring-tensile tests and Brazilian tests (Wang et al., 2004; Aly et al., 2019; Weeks, 2010). A typical Brazilian test is that loads are applied symmetrically on materials with a disc shape, where a tensile strength forms and initials splitting failures in the sample (Rocco et al., 1999; Yu et al., 2018). Evidence suggests that the Brazilian tests have advantages on the tensile strength determination of rocks (ASTM, 2008). Ming et al.(2015) and Wang et al. (2004) showed that there are possibilities to obtain both tensile and compressive elastic modulus by Brazilian tests (Wang et al., 2004; Ming et al., 2017). The Brazilian tests were also performed on obtaining tensile strength of frozen soils (Zhou et al., 2015; Ming et al., 2017; Liu et al., 2018). Kovacs and Kalafut (1977) studied the tensile strength through the Brazilians tests with a hydraulic rig. However, the inconstant loading speed made it difficult to consider viscous deformation during loading. And the results were expected to have some error compare with results from uniaxial tensile tests. Rocco an others (1999) suggested a modified solution when the loading status becomes distributed loads from pointed loads.

Considering Brazilian tests have not been thoroughly carried out on the sea ice, there has been arisen the following two essential questions: 1). If the Brazilian tests are an appropriate approach to determine ice tensile strength; 2). How much difference between the uniaxial tension tests and the Brazilian tests. To study these two questions, the Brazilian tests were carried out to investigate the tensile strength of the granular sea ice in the Bohai Sea.

2. EXPERIMENT DESCRIPTION

To study the tensile strength, the Brazilian tests were performed on the landfast sea ice in the Bohai Sea. The principle function of a Brazilian device is to provide a compression load, thus most equipment for uniaxial compression tests can be proposed. As shown in Fig.1, the bottom seating moved upward with a constant speed while the top platen is fixed by a load cell. The loads and displacement were recorded simultaneously.



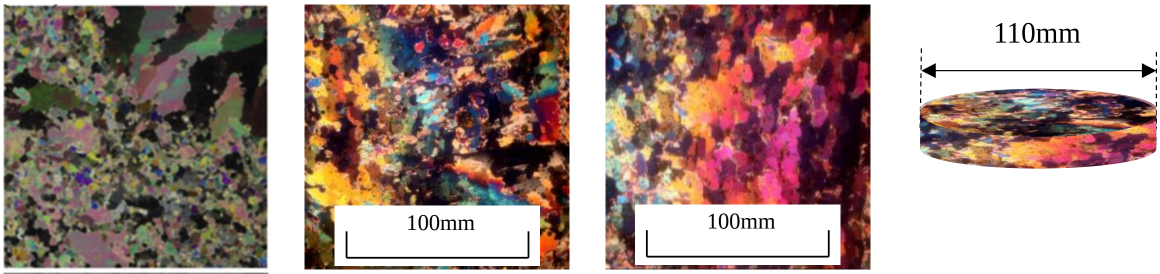
(a) Scheme of the tests device

(b) Brazilian test of an ice disc (D=110mm)

Figure 1. Brazilian testing arrangements

Under the driven of wind and current, ice sheets may drift against to each other and form slash ice by crushing (Bonath et al, 2018). The ice debris later refreeze together to have a granular structure, as shown in Fig.2(a). The ice collected in this paper belonged to this type based on its texture (Fig.2(b) and (c)), which shows that the grain diameter is around 5-10mm. Samples were cored from ice covers and then milled to discs of 110±2mm in diameter and 30-62mm in thickness, as shown in Fig.2(d).

A total of 40 ice discs were performed at temperature from -4ºC to -32 ºC. There were two loading speed 0.1mm/s and 0.04mm/s. After each test, the sample salinity was measured from the liquid conductivity while the density was obtained by hydrostatic weighting (Pustogvar and Kulyakhtin, 2016). The average salinity and density are 6.7±3.1‰ and 849±52kg/m^3, respectively. And the total porosity was further calculated based on the suggestion of Cox and Weeks (1983). Table 1 shows the distribution of brine volume and total porosity.



(a) Ice texture of crushed ice (Bonath et al, 2018) (b) Ice texture in horizontal orientation (c) Ice texture in vertical orientation (d) Structure of an ice disc

Figure 2. The structure of ice samples

Table.1 The distribution of brine volume and total porosity

Brine volume	Percentage	Total porosity	Percentage
<10‰	7.89%	<20‰	7.89%
10‰~30‰	60.5%	20‰~40‰	39.47%
30‰~50‰	18.4%	40‰~60‰	36.84%
50‰~70‰	10.5%	60‰~80‰	13.16%
>70‰	2.6%	>80‰	2.63%

In a Brazilian test, compressive line loads are symmetrically applied on a disc, as shown in Fig.3. Since the sample thickness is smaller than its diameter, it can be simplified into a quasi 2-D problem. Then, the line loads become to concentrated loads as denoted by P in Fig.3.

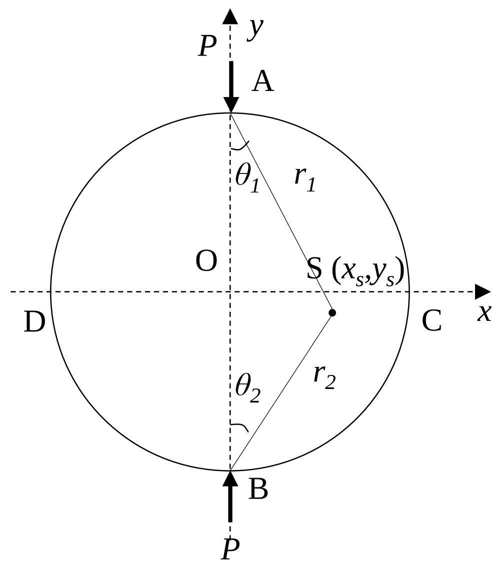


Figure 3. The schematic showing stress distribution within an disc

For an isotropic disc subjected to concentrated loads, the analytical solution is described by Muskhelishvili (1955):

$$\sigma_x = \frac{2P}{\pi L}\left[\frac{\sin^2\theta_1\cos\theta_1}{r_1} + \frac{\sin^2\theta_2\cos\theta_2}{r_2}\right] - \frac{2P}{\pi DL} \tag{1}$$

$$\sigma_y = \frac{2P}{\pi L}\left[\frac{\cos^3\theta_1}{r_1} + \frac{\cos^3\theta_2}{r_2}\right] - \frac{2P}{\pi DL} \tag{2}$$

where σ_x and σ_y are normal stresses in x-direction and y-direction; r_1 and r_2 are the distances from selected point S to the loading contact points A and B; θ_1 and θ_2 are their the angles to y-direction; P is the concentrated load; D is the disc diameter; L is the disc thickness.

When the point S is on the y-axis(x=0), then Eq.(1) and Eq.(2) become:

$$\sigma_x = -\frac{2P}{\pi DL} \tag{3}$$

$$\sigma_y = \frac{2P}{\pi L}\left[\frac{1}{r_1} + \frac{1}{r_2}\right] - \frac{2P}{\pi DL} \tag{4}$$

Based on Eq.(3), the ASTM suggest the tensile strength for rocks and concretes is:

$$\sigma_b = -\frac{2P_{\max}}{\pi DL} \tag{5}$$

where $\underline{P_{max}}$ is the maximum load and σ_b is the tensile strength.

The Eqs.1-5 are assumed to be based on two opposite point loads. However, sea ice is a viscous material, the contact area deforms during loading, as shown in Fig.4. The theoretical solution may not available due the point loads become distributed loads. In this case, Rocco and others suggest to modify Eq.5 with a parameter β (Rocco et al., 1999):

$$\beta = \frac{w}{D} \tag{6}$$

$$\sigma(\beta < 0.16) = \frac{2P_{\max}}{\pi DL}\left(1-\beta^2\right)^{3/2} \tag{7}$$

where w is the width of the deformation on the disc.

If we assume the deformation only appears at the sample-plate contact area, the width of the deformation is dependent on the displacement of the plates, as shown in Fig.4. Since the loading speed is constant, the w can be calculated by:

$$w = \sqrt{\left(\frac{D}{2}\right)^2 - r_f^{\,2}} \tag{8}$$

$$r_f = \frac{D - \int v dt}{2} \tag{9}$$

$$w = \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D - \int v dt}{2}\right)^2} \tag{10}$$

where r_f is the radius when failure happens; v is the moving speed of the plates.

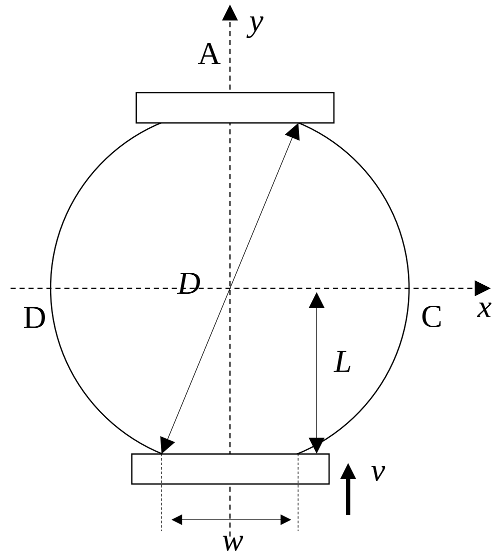


Figure 4. The schematic of deformation on contact area

3. RESULTS & DISCUSSION

In this part, the author will introduce the failure process and influences of loading rate, temperature and porosity on ice tensile strength.

3.1 Failure pattern

The experiments were performed on different conditions (temperature, loading speed, thickness). All the samples were failed in splitting pattern, as shown in Fig.4. Overall, the dominating cracks concentrated in the center with some curvatures (e.g. No.4, No.6, No.11 tests). It is because the crack preferred to develop on the grain boundaries and it altered the failure path. When the initial deficiency is close to the edge (Left part of No.8 sample), it did not play roles in the failure process, since the tensile stress was stronger in the center. It also can be observed that sample deformed or even crushed at ice-platen contact area. That means, when the failure occurred, the sample was actually under a distributed load, which is simplified as a concentrated load. And this simplification may lead to some error on the calculation of tensile strength. The overall failure process argue that the stress states agreed with the analytical solution in Eq.(1) and (2). Therefore, it is available to determine ice tensile strength through the Brazilian tests.

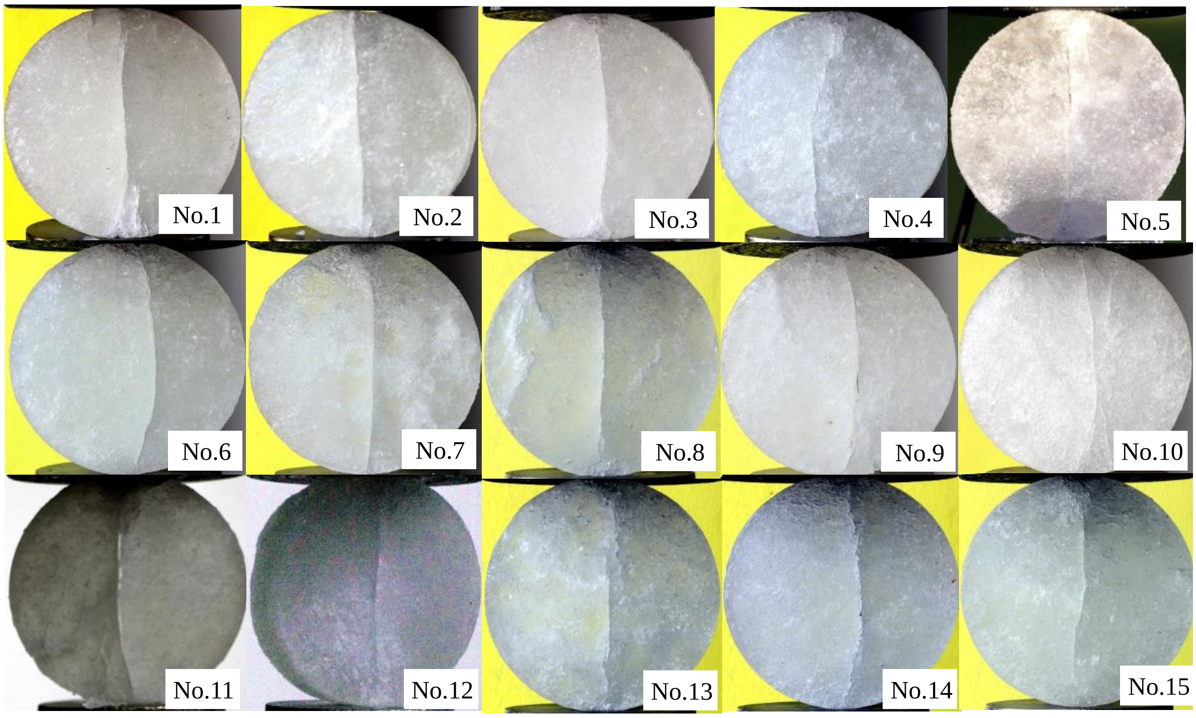
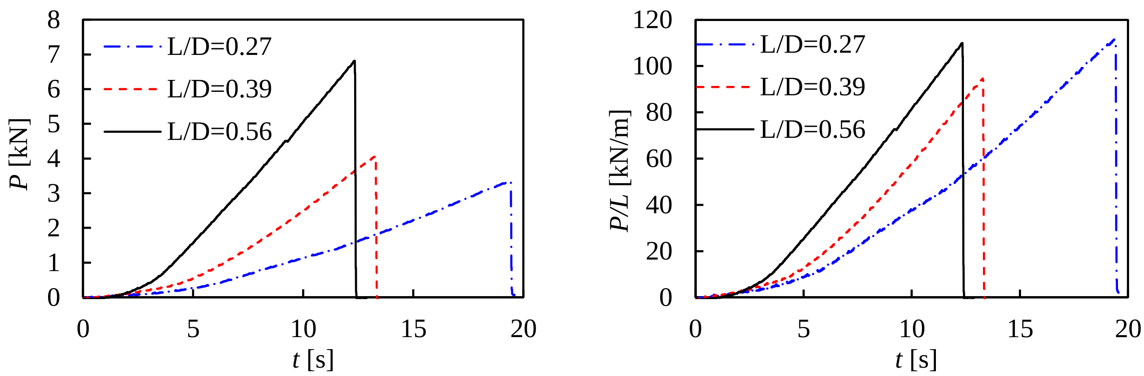


Figure 4. Failure pattern of ice samples

3.2 Effect of disc thickness

The ratio between disc thickness and diameter (*L/D*) is an important parameter for the Brazilian tests. For a high *L/D* value, the analytical solution based on the 2-D assumption may not be available. For a low value of *L/D*, the discs may fail in buckling instead of splitting.

Fig.5(a) gives the time history curves under various *L/D*. It is reasonable that the thicker sample bears higher load to reach the tensile strength. If we divide the load to the thickness (*L*), the line loads are obtained in Fig.5(b). It shows that there is no strong correlation between tensile strength and *L/D*. However, the slopes of these curves (Fig.5(b)) have positive correlation with *L/D*. This might be due to the high thickness constrained the deformation and induced a 3-D effect. The time histories together with the sample failure pattern argue that the *L/D* ratio values (in this paper) are suitable for testing ice tensile strength.

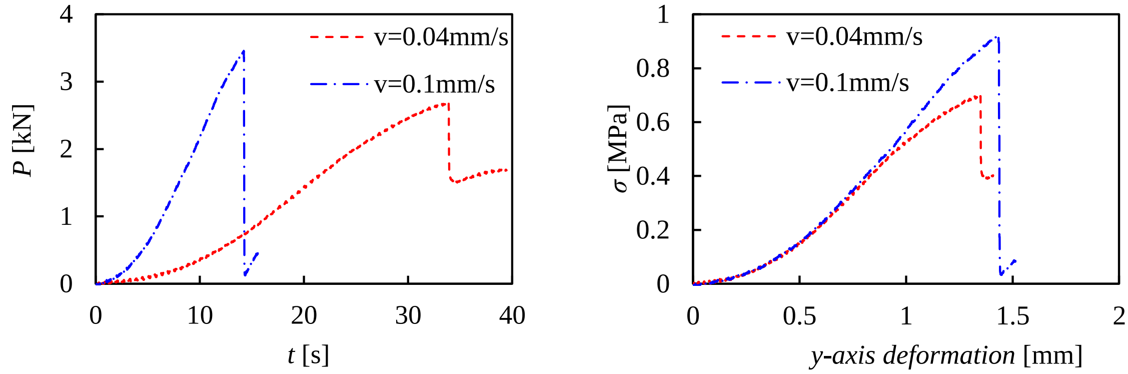


(a) Loading time history under various *L/D* (b) Line load time history under various *L/D*

Figure 5. The influence of *L/D* on tensile strength

3.2 Effect of loading rate

Although the main target is to determine the tensile strength, the samples carries both tensile and compressive stresses. As we all know, both the compressive stress and effective Elastic Modulus are sensitive to strain rates in uniaxial compression tests. Thus, we compare the time histories of different loading speeds (0.04mm/s and 0.1mm/s) in Fig.6. The results show that the tensile strength are little influenced by the loading rate, which is agreed with measurements from uniaxial tension tests of sea ice (Richter-Menge and Jones 1993). If we plot tensile stress against deformation on y-axis, Fig.6(b) shows the two curves follow a similar path. It may because the two values (0.1mm/s, 0.04mm/s) are closed to each other. The results suggests that the loading speed has very little influence on tensile strength.



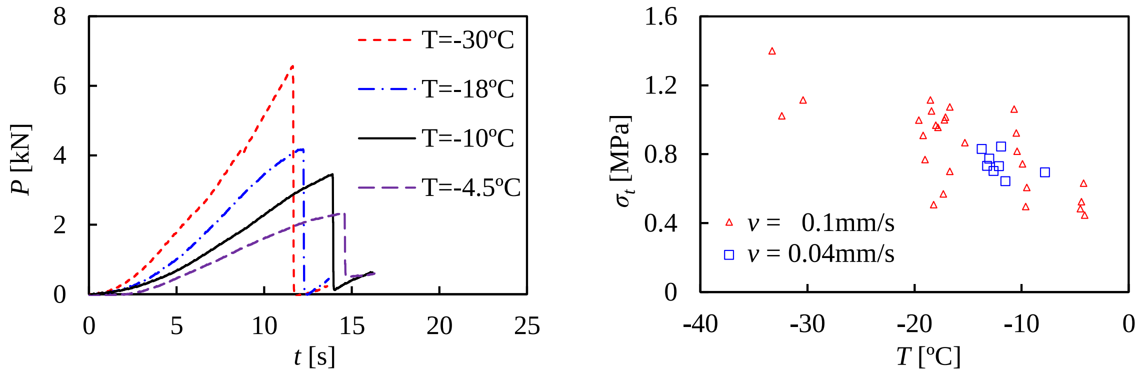
(a) Loading time history under various loading rates

(b) The relation between loads and deformation

Figure 6. The influence of loading rate on tensile strength

3.3 Effect of temperature

Generally, the sea ice strength is sensitive to temperature since it is related to brine volume. In Fig.7(a), it shows that the slope becomes steeper for lower temperature. It means the discs become stiffer at low temperature. Fig.7(b) shows the relation between tensile strength and temperature. It is no surprise that the tensile strength decreased with increasing temperature. At low temperature, some brine becomes solid ice, which carries higher tension than liquid water. Besides, the Fig.7(b) also shows the results from two loading speed give the same trend. When taken together, these results suggest that there is a negative correlation between temperature and tensile strength.



(a) Loading time history under different temperature

(b) The relation between tensile strength and temperature

Figure 7. The influence of ice temperature on tensile strength

3.4 Effect of porosity

There have been a few tests performed to measure tensile strength on laboratory grown ice and sea ice. Based on previous uniaxial tension tests, Timco and Weeks (2010) fit an expression between tensile strength and porosity for horizontally-loaded samples (Timco and Weeks, 2010):

$$\sigma_{b\_H} = 4.278 v_t^{-0.6455} [\text{MPa}] \tag{11}$$

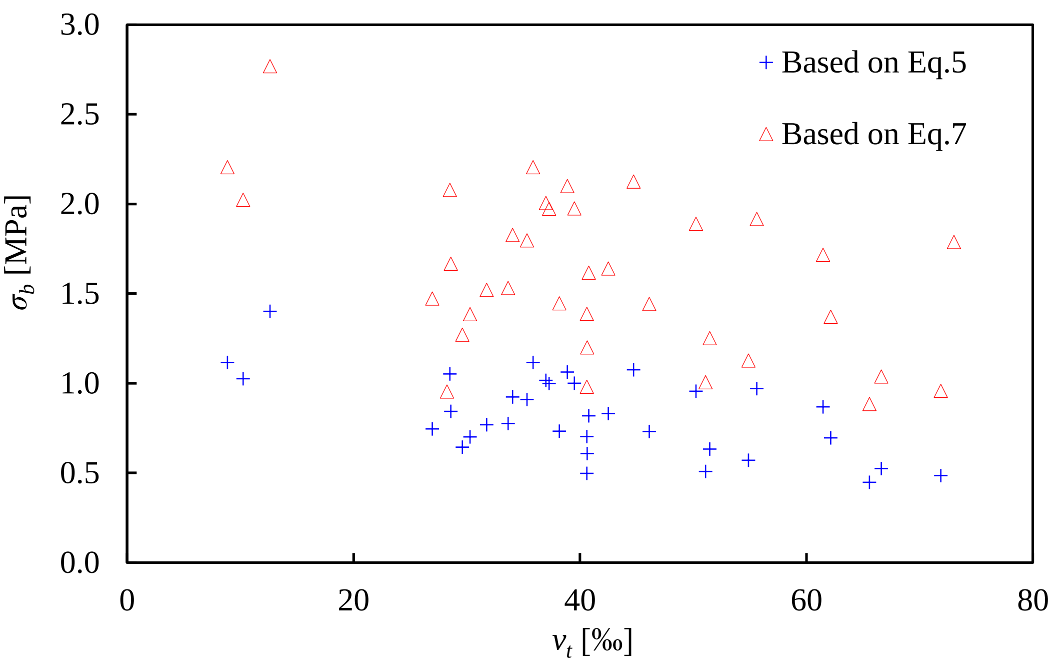
where σ_{b_H} is the tensile strength for horizontal orientated samples; v_t is ice porosity.

Based on the results from Keuhn et al (1990), it shows that the vertical orientated samples have a tensile strength three to four times larger than that of horizontal orientated samples (Kuehn et al., 1990). If we assume the ratio is also suitable for the fitting curve from Timco and Weeks (2010), then the vertical orientated samples have a tensile strength:

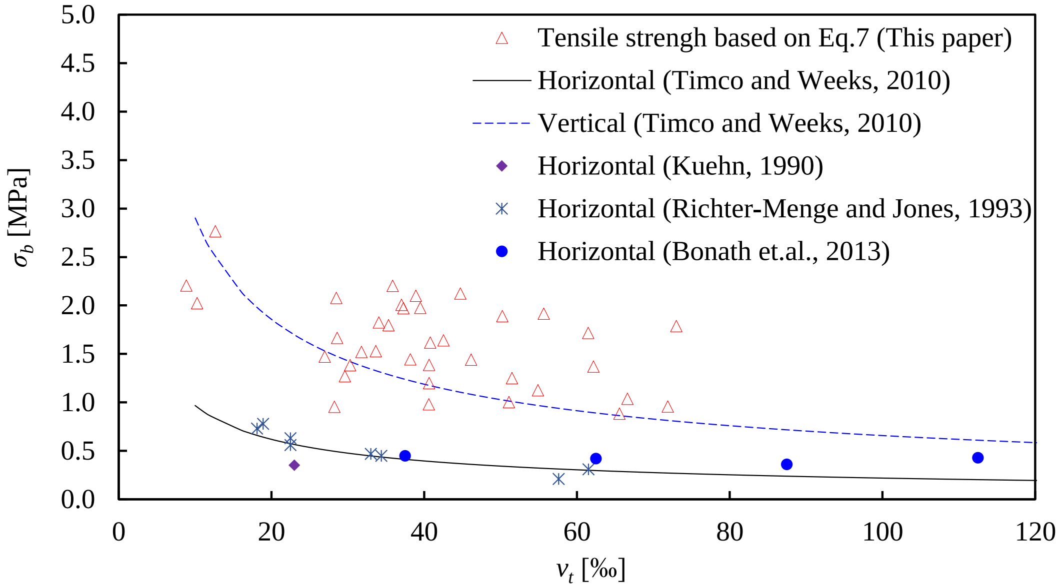
$$\sigma_{b\_V} = 3 \cdot \sigma_{b\_H} \tag{12}$$

Several reports have related tensile strength to total porosity. It is because a higher porosity indicates low solid content to carry the stresses, as the discussion in Sec.3.3. In Fig.8, the tensile strength from this paper and other reports are plotted against total porosity. In Fig.8(a), the tensile strength is calculated with Eq.5 and Eq.7, respectively. For the same condition, the values from Eq.7 are about two times higher than that from Eq.5. It means that the tensile strength may be overestimated without the consideration of local deformation of ice discs.

Overall, the tensile strength decreased with increasing porosity. Results from previous studies with uniaxial tensile tests are also plotted in Fig.8(b). It shows that the tensile strength from the Brazilian tests is generally higher than previous values in both horizontal loading (solid line in Fig.8(b)) and vertical loading (dashed line in Fig.8(b)). Normally, the granular ice may stronger than the columnar ice under horizontal loading, but not under vertical loading. Therefore, it is reasonable to assume that the tensile strength from the Brazilian tests are higher than uniaxial tensile tests.



(a) The tensile strength based on different assumptions



(b) The comparison with the results from unaxial tensile tests

Figure 8. The relation between total porosity and tensile strength

4. CONCLUSIONS

Based on previous results in this study, the main conclusions can be drawn as following:

1). The calculated tensile strength varied from 1MPa to 3MPa and decreased with increasing total porosity. The value for granular ice is higher than the uniaxial tensile test from previous studies.

2). For the loading speeds 0.1mm/s and 0.04mm/s, it shows the loading speed has very little influence on tensile strength.

3). In the Brazilian tests, all the samples failed in splitting, which denoted that the sample center is distributed with strong tensile stresses.

4). The experiments show that the ice discs deform during loading. The neglect of the deformation may lead to underestimation of tensile strength.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of master student Qingyu Jiang and Fengyuan Zhao for ice collecting and testing, crew of Marine Environmental Forecasting Station of Bayuquan. The work was supported by National Key Research and Development Program of China (Grant No. 2106YCF1401505).

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