Experimental Studies on Elastic Modulus and Flexural Strength of Sea Ice in the Bohai Sea

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Abstract: This paper deals with measurements of the elastic modulus and the flexural strength of sea ice collected at nine sites in the Bohai Sea in the two consecutive winters of 2008–2010. Experimental results show that both elastic modulus and flexural strength increase with a decrease of brine volume and have an exponential relationship with brine volume. The elastic modulus is independent of stress rate, but the flexural strength increases linearly with the increase of stress rate. This paper presents a single-parameter (i.e., brine volume) exponential equation for the elastic modulus and a two-parameter (i.e., brine volume and stress rate) exponential equation for the flexural strength, respectively. Finally, the relationship between the elastic modulus and the flexural strength is discussed. **DOI: 10.1061/(ASCE)CR.1943-5495.0000035.**

CE Database subject headings: Ice; Oceans; Elasticity; Flexural strength; China; Experimentation.

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Introduction

The ice load is an important environmental load during the design, construction, and in-service process of offshore structures. The amplitude of ice load is not only related to the shape and size of the offshore structure itself, but is also affected by the physical and mechanical properties of sea ice. The salinity, density, and

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temperature of sea ice, influenced by local meteorological and hydrological conditions, are different in different sea regions. In addition, these physical properties affect mechanical properties of sea ice, such as compressive, flexural, and shear strength (Ding 1999; Timco and Weeks 2010).

Bending failure is a predominant failure mode in a number of ice/structure interactions, such as jacket platforms with ice-breaking cones, manufactured islands, slope protection, and ice breakers (Qu et al. 2006). The ice load amplitude is dominated by sea ice flexural strength and affected by sea ice elastic modulus. Moreover, the breakup, ride-up, rafting, and ridge-building of sea ice under wave, wind, and current actions, and the bearing capacity of sea ice covers, are closely related to both elastic modulus and flexural strength (Kovacs and Sodhi 1980; Masterson 2009). Therefore, it is important to study elastic modulus and flexural strength of sea ice in sea ice research.

For the elastic modulus and flexural strength of sea ice, two bending experimental approaches have been developed. One is cantilever beam tests and the other is simple beam tests (Weeks and Anderson 1958; Schwarz et al. 1981; Frederking and Timco 1983; Parsonsa et al. 1992; Timco and O'Brien 1994; Barrette et al. 1999). Normally, the cantilever tests are performed in situ, and have two advantages: they are relatively easy to perform on a large beam and can maintain the temperature gradient in the ice sheet (Timco and Weeks 2010). The simple beam tests are conducted in situ or in the laboratory, and ice samples can be loaded at three or four equidistant points (Timco and O'Brien 1994; Barrette et al. 1999; Timco and Weeks 2010).

The elastic modulus of sea ice has been investigated with bending experiments in previous studies, and the influences of ice temperature, salinity, and stress rate have been analyzed. Barrette et al. (1999) found the elastic modulus has a close relationship with square root of brine volume. Timco and Weeks (2010) pointed out the elastic modulus decreases as a linear function of brine volume. Frederking and Timco (1983) found that the elastic modulus of freshwater ice increases with increasing stress rate through cantilever beam tests. Other experimental results, however, provided no evidence that stress rate has any influence on the elastic modulus (Zhang et al. 1993; Sui et al. 1996; Barrette et al. 1999).

As a complex crystal material, sea ice flexural strength is affected by many factors. Different test conditions, such as the choice of test type, loading direction and sample size, produced different results (Frederking and Timco 1983; Timco and O'Brien 1994; Kermani et al. 2008). Weeks and Anderson (1958) tested the influence of salinity and temperature, respectively. They found that the flexural strength increases with the decrease of salinity and temperature. Zhang et al. (1993) and Blanchet (1997) also reported a linear relationship between ice temperature and the flexural strength. Timco and O'Brien (1994) summarized 939 flexural strength tests and pointed out that the flexural strength of sea ice has a negative exponential relationship to the square root of brine volume. In the experiment of Barrette et al. (1999), a similar equation was obtained, although the strength value was a bit larger. However, other research has shown that the flexural strength of sea ice is a linear function of the square root of brine volume (Sui et al. 1996; Blanchet 1997). Limited work has been devoted to the influence of stress rate. Frederking and Timco (1983) reported that stress rate has little influence on the sea ice flexural strength. The reason for this might be the lack of experimental data (Timco and Weeks 2010).

In the tests of Gagnon and Gammon (1995), the sea ice flexural strength increased with increasing stress rate. However, previous studies have focused on the influence of a single factor on the flexural strength of sea ice. In fact, these influential factors are coupled together.

During the 1980s and 1990s, physical and mechanical properties of sea ice were comprehensively investigated in the Bohai Sea of China. Basic characteristics of elastic modulus and flexural strength were analyzed (Yue 1991; Ding 1999). A linear relationship between the flexural strength and square root of brine volume was obtained. The sensitivity of the flexural strength to stress rate was also discussed. The studies showed that sea ice flexural strength first increases and then decreases with the increase of stress rate (Zhang et al. 1993; Sui et al. 1996). The elastic modulus is in the range of $0.3 \sim 2.5$ GPa and is independent of stress rate (Zhang et al. 1993; Sui et al. 1996). However, most of these experiments were conducted at only one or two local sites in the Bohai Sea. In particular, little work has been done on sea ice in the Bohai Sea during the past 10 years. With the rapid increasing gas/oil exploitation and development in the Bohai Sea recently, there is an urgent requirement for the experimental investigation of physical and mechanical parameters of sea ice.

Therefore, the writers selected nine sites in the Bohai Sea, measured ice salinity and temperature, and analyzed the elastic modulus and flexural strength through simple beam tests during the two winters of 2008–2010. This study examined the influence of brine volume and stress rate on the elastic modulus and flexural strength, respectively. In particular, the coupling effect of these influential factors on the sea ice flexural strength is discussed.

Measurement Sites and Sample Collection

During the two consecutive winters of 2008–2010, the physical and mechanical properties of sea ice in the Bohai Sea were measured. Fig. 1 shows the field test and sample collection sites. The nine sites are divided into 3 groups according to their geographic locations. Four are in Laizhou Bay: Site A of Haihong Harbor, Site B of Guanhai Jetty, Site C of Hongguang Quay, and Site D of Xiaodao River. Two are in Liaodong Bay West: Site E of NanbaoTown and Site F of Xingcheng City. Liaodong Bay East has three: Site G of Bayuquan, Site H of Dazuizi, and Site I of Changxing Island. The fast level ice was selected for sampling. Except for Sites F and G, where only laboratory tests were performed, both laboratory and field tests were conducted for the other seven sites. Table 1 lists the field measurement data.

Experimental Methods

A three-point simple beam bending test was adopted, as shown in Fig. 2, where L is the ice sample length, L_0 is the distance between the two fixed supporting points, h is the sample height, and b is the width. The axis of the beam was arranged to be parallel to the ice cover surface when the sample was cut from the ice cover. The upper ice cover surface was placed as the top side of the beam, and the load was applied at the middle point on the top side of ice beam. This was to ensure that the loading direction was parallel to the ice crystal axes and the bottom surface of ice

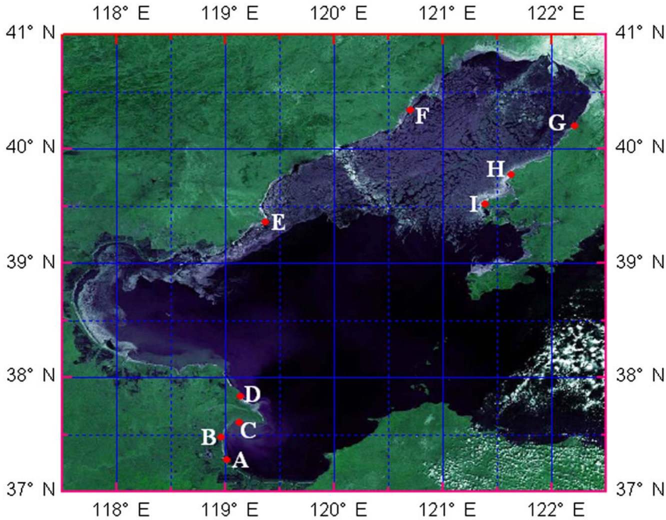


Fig. 1. Field measurement and sample collection sites

Table 1. Field Measurement Data

Field tests sites		Sampling date	Sample numbers for flexural strength tests	Sample numbers for elastic modulus tests	Ice thickness (cm)	Air temperature (°C)	Mean ice salinity (‰)
Laizhou Bay	AHaihong	2009-01-23	6	6	20	−11.1	6.3
		2010-01-22	27	21	17	−4.5	4.7
	BGuanhai	2009-01-21	21	5	15	−6.5	5.6
	CHongguang	2009-01-20	8	5	11	−2.0	5.6
		2010-01-22	24	22	20	−3.3	5.3
	DXiaodaohe	2010-01-21	22	20	33	−5.5	4.1
Liaodong Bay-West	ENanbao	2010-01-23	12	5	32	−5.4	5.8
	FXingcheng	2009-02-01	15	4	15	−5.0	4.4
Liaodong Bay-East	GBayuquan	2009-02-12	5	5	28	−9.0	4.8
	HDazuizi	2009-02-02	5	5	30	−2.5	4.3
	I Changxingdao	2009-02-02	11	4	18	−1.5	4.1

cover was in tension. The middle part of the ice sheet was cut to $700 \times 75 \times 75$ mm rectangular parallelepiped samples and processed for low temperature laboratory tests. The specimen temperature in the laboratory tests was controlled by the cold storage and cold box of the testing machine. Local indentions at the loading and supporting points sometimes appeared, but their influence on the elastic modulus and flexural strength was neglected because they were not obvious.

The deflection of the loading point could then be measured with a displacement meter on the indenter. With the measured stress-deflection curve of an ice sample,

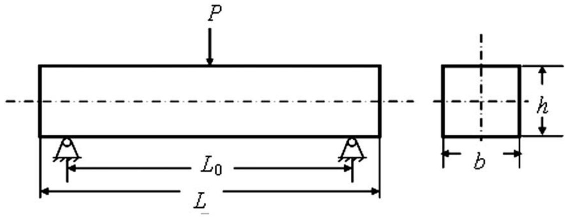


Fig. 2. Three-point bending test

the elastic modulus and flexural strength can be calculated simultaneously with the same ice sample.

The elastic modulus E can be derived from the measurements of stress and deflection at the load action point as

$$E = \frac{L_0^2}{6h} \frac{\sigma_B - \sigma_A}{u_B - u_A} \tag{1}$$

where σ_A, σ_B, u_A, and u_B = corresponding stresses and deflections of the load action point when the applied load is P_A and P_B, respectively.

The flexural strength σ_f can be calculated as

$$\sigma_f = \frac{3}{2} \frac{P_{\max} L_0}{bh^2} \tag{2}$$

where $P_{\max}$ = maximum load when ice fails and can be obtained from the measured load-time curve.

The stress rate $\dot{\sigma}$, as an index of loading rate, ranged from 0.03 to 1.65 MPa/s in the tests, which can be achieved via manipulative control of the indenter velocity until the beam fails. In the calculations, the stress rate can be determined by the stress-time curve as follows:

$$\dot{\sigma} = \frac{\sigma_B - \sigma_A}{t_B - t_A} \tag{3}$$

where t_B and t_A = corresponding loading time of stresses σ_A and σ_B, respectively.

Fig. 3(a) shows a typical stress-deflection and Fig. 3(b) shows a stress-time curve measured at the ice temperature of $-8.6\,°\mathrm{C}$. Thus, the elastic modulus is 0.72 MPa, the flexural strength is 1.16 MPa, and the stress rate is 0.37 MPa/s, based on Eqs. (1)–(3).

Influences of Brine Volume and Stress Rate on Elastic Modulus

In this study, the influences of brine volume and stress rate on the sea ice elastic modulus were analyzed based on 102 tests measured in the Bohai Sea during the two winters of 2008–2010.

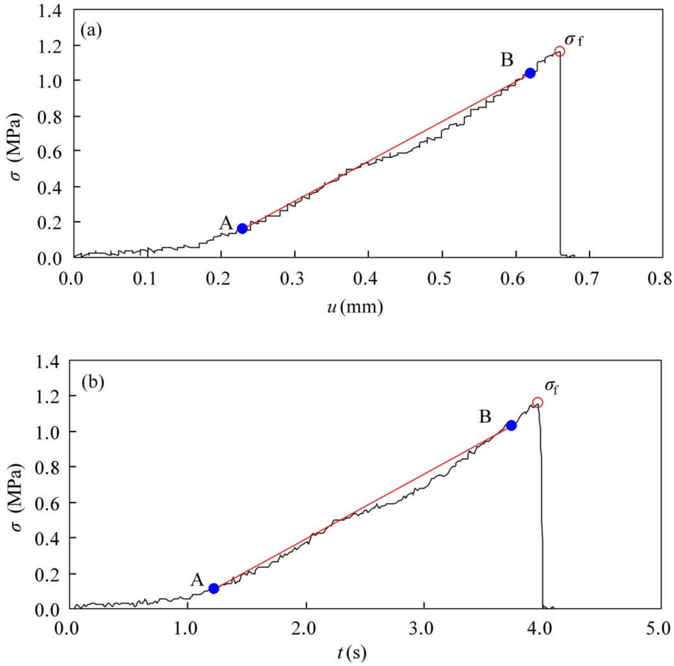


Fig. 3. (a) Stress-deflection measured with bending experiment of sea ice; (b) stress-time curve measured with bending experiment of sea ice

Influence of Brine Volume

Brine volume is a function of temperature and salinity, and can be determined with (Frankenstein and Garner 1967)

$$\nu_b = S\left(0.532 + \frac{49.185}{|T|}\right) \qquad (-0.5\,℃ \geq T \geq -22.9\,℃) \tag{4}$$

where T = ice temperature (℃); and S = ice salinity (‰).

Fig. 4 plots the elastic modulus against square root of brine volume, and an exponential fit to the data yields

$$E = 1.43e^{-5.61\sqrt{\nu_b}} \tag{5}$$

with an $R^2 = 0.36$, which is high given the natural variability in sea ice itself.

Figs. 5(a) and 5(b) show $E - S$ and $E - T$ plot, respectively. For the analysis of the influence of salinity only, ice temperature was divided into two groups: $-15.5 \sim -6.0\,℃$ and $-6.0 \sim -2.0\,℃$. Similarly, salinity was divided into two groups of $2.0 \sim 5.0$‰ and $5.0 \sim 7.0$‰ for the analysis of the influence of temperature only. For both groups of ice temperature and salinity, the elastic modulus

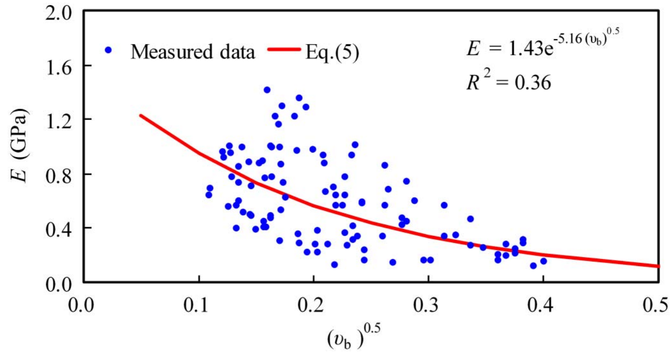


Fig. 4. Elastic modulus versus square root of brine volume

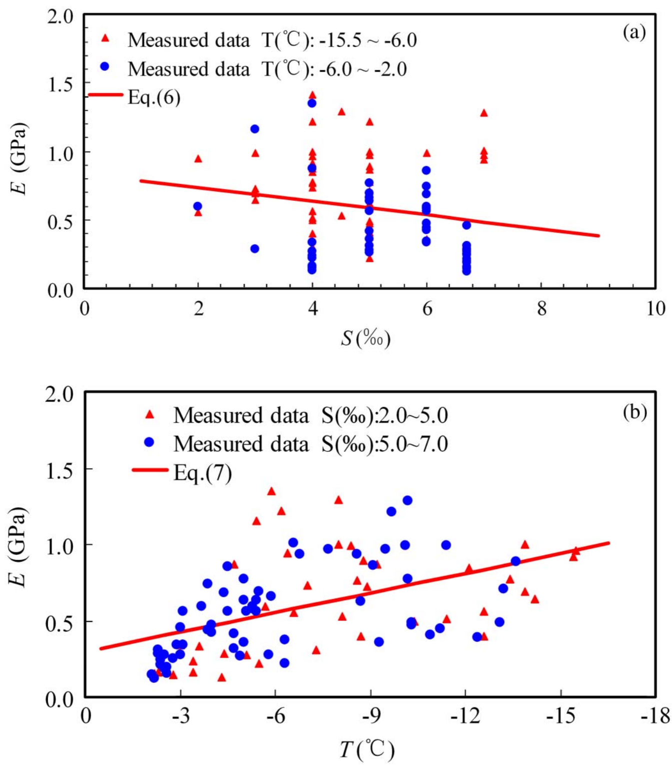


Fig. 5. (a) Elastic modulus versus salinity; (b) elastic modulus versus temperature

shows a considerable amount of scatter. The $E-S$ and $E-T$ relationship can be fitted by a linear function as

$$E = 0.835 - 0.050S \tag{6}$$

$$E = 0.295 - 0.043T \tag{7}$$

with the correlation coefficients $R^2 = 0.037$ and 0.242, respectively. Both are less than that of brine volume on the elastic modulus with $R^2 = 0.36$. Therefore, it is more reasonable to predict the elastic modulus of sea ice in the Bohai Sea with the consideration of influence of brine volume, which includes both ice temperature and salinity.

Influence of Stress Rate

Fig. 6 plots the elastic modulus versus stress rate, and a linear fit to the data produces

$$E = 0.568 + 0.013\dot{\sigma} \tag{8}$$

with the correlation coefficient $R^2 = 0.0008$. This indicates that the elastic modulus of sea ice is independent of stress rate in the Bohai Sea.

Influences of Brine Volume and Stress Rate on Flexural Strength

Similar to the elastic modulus, the flexural strength of sea ice also has a close relationship with brine volume and stress rate. In this study, the coupled influence of brine volume and stress rate on sea ice flexural strength was examined based on bending test results in the Bohai Sea.

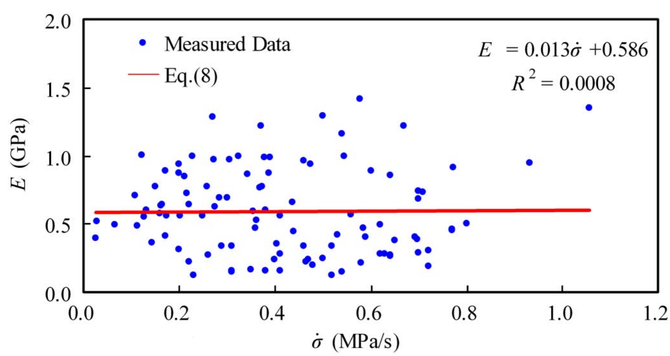


Fig. 6. Elastic modulus versus stress rate

Influence of Brine Volume Only

Fig. 7 plots the results of the flexural strength versus square root of brine volume, and an exponential fit to the data yields

$$\sigma_f = 2.41e^{-4.29\sqrt{v_b}} \tag{9}$$

with the correlation coefficient $R^2 = 0.52$. In the study of Timco and O'Brien (1994), $\sigma_f = 1.76e^{-5.88\sqrt{v_b}}$ with $R^2 = 0.77$. The curve of Timco and O'Brien (1994) is also included in Fig. 7 for comparison. It shows that the flexural strength in the Bohai Sea is a little higher than that of Timco and O'Brien (1994). This may be attributable to the smaller sample size used, which will increase the flexural strength. Other reasons may be attributed to the higher stress rate used, the different crystal structure of sea ice on micro scale, and air volume. The sea ice samples were collected at nine different sites around the Bohai Sea and have different physical properties. Therefore, the flexural strength presents a relatively large scatter with different brine volume, even measured with the same sample size and test method in this paper.

Figs. 8(a) and 8(b) plot the results of σ_f against S and σ_f against T, respectively. The $\sigma_f - S$ and $\sigma_f - T$ relationship can be described through a linear curve fitting as

$$\sigma_f = 1.26 - 0.081S \tag{10}$$

$$\sigma_f = 0.35 - 0.09T \tag{11}$$

with the correlation coefficient $R^2 = 0.042$ and 0.527, respectively. It indicates that the flexural strength has a more close relationship with ice temperature.

Influence of Stress Rate Only

Fig. 9 shows the flexural strength versus stress rate. To reduce the influence of brine volume, the results are plotted via three groups of $\sqrt{\upsilon_b}$ as $0.1 \sim 0.2$, $0.2 \sim 0.3$, and $0.3 \sim 0.5$. In this way, it shows σ_f is linearly related to $\dot{\sigma}$ with relatively close

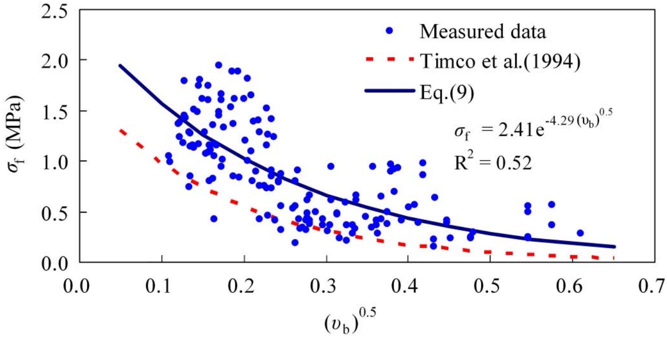
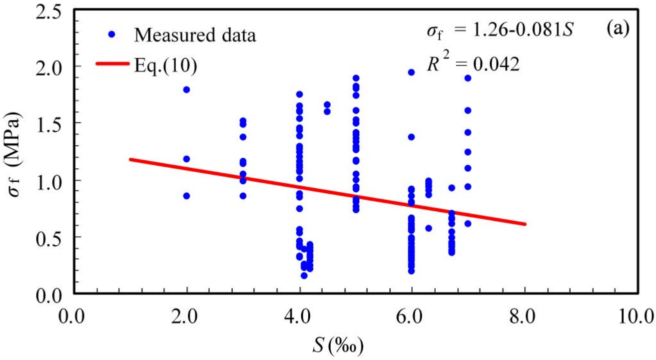


Fig. 7. Influence of brine volume on flexural strength



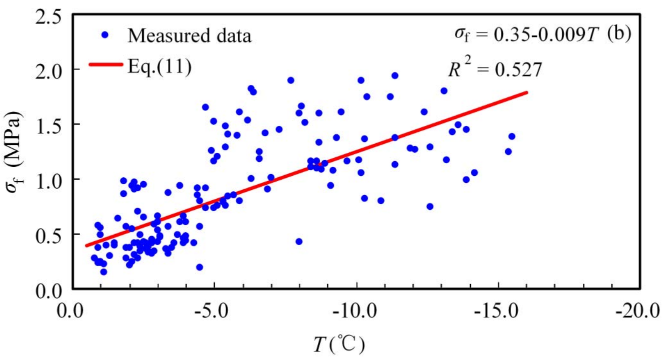


Fig. 8. (a) Influence of ice salinity on flexural strength; (b) influence of ice salinity on flexural strength

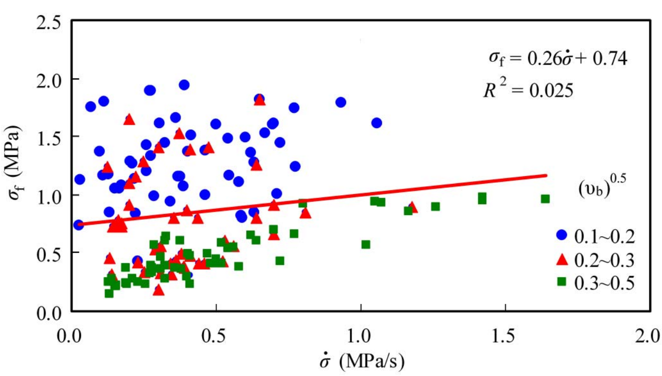


Fig. 9. Influence of stress rate on flexural strength

brine volume values. This is more obvious for the range of 0.3 ~ 0.5. Therefore, it can be inferred that σ_f and $\dot{\sigma}$ are linearly related with the same brine volume values.

A linear relationship between the flexural strength and stress rate is fitted as

$$\sigma_f = 0.74 + 0.26\dot{\sigma} \tag{12}$$

with the correlation coefficient $R^2 = 0.025$.

Coupling Effect of Brine Volume and Stress Rate

Fig. 10 plots the three-dimensional distribution of σ_f, $\sqrt{v_b}$, and $\dot{\sigma}$ to examine the coupling effect of $\sqrt{v_b}$ and $\dot{\sigma}$ on σ_f. It shows that σ_f increases with the decrease of $\sqrt{v_b}$ and with the increases of $\dot{\sigma}$. It can thus be assumed that σ_f is a function of $\sqrt{v_b}$ and $\dot{\sigma}$ as

$$\sigma_f = (a + b\dot{\sigma})e^{(c+d\dot{\sigma})\sqrt{v_b}} \tag{13}$$

where a, b, c, and d = surface fitting parameters to be determined. Based on the experimental results, $a = 2.58$, $b = 0.07$, $c = -5.54$, and $d = 2.00$ were obtained. Further analysis showed that the effect of the coefficient b was minimal. Here, the influence of parameter b was ignored, and Eq. (13) can be simplified as

$$\sigma_f = ae^{(c+d\dot{\sigma})\sqrt{v_b}} \tag{14}$$

with $a = 2.61$, $c = -5.58$, and $d = 2.09$.

Fig. 11 shows the surface of the flexural strength with smoothing curve fitting with $R^2 = 0.59$, which is higher than 0.52 in Fig. 7 and 0.025 in Fig. 9, where only $\sqrt{v_b}$ and $\dot{\sigma}$ are considered, respectively. Therefore, it is more appropriate to conduct

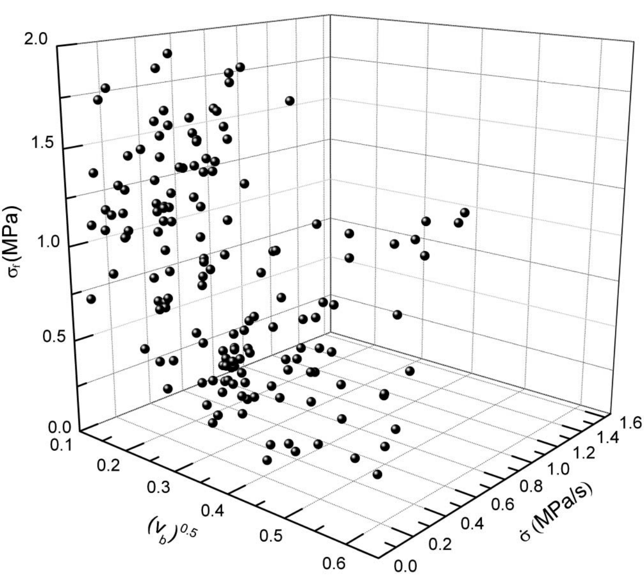


Fig. 10. Three-dimensional distribution of flexural strength

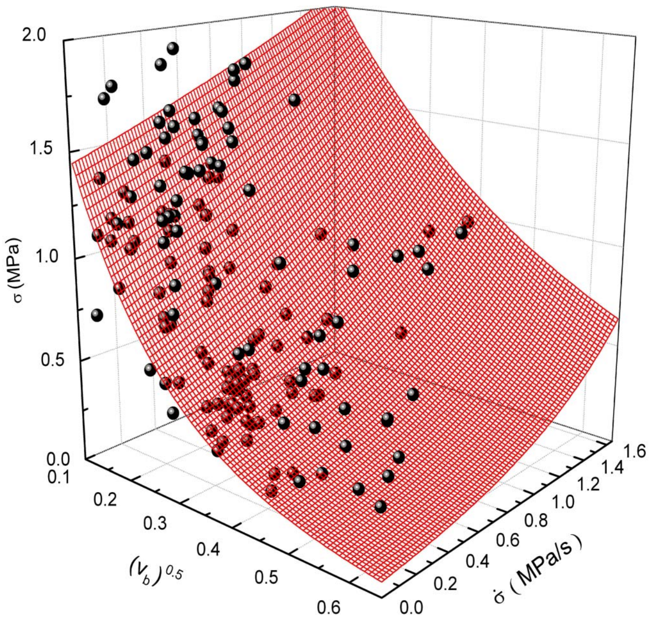


Fig. 11. Curve-fitted flexural strength surface

double-parameter analysis of brine volume and stress rate on the flexural strength of sea ice in the Bohai Sea.

Relationship between Elastic Modulus and Flexural Strength

The ratio of the elastic modulus to the flexural strength is also a parameter that reflects the flexural behavior of the floating ice sheet during its interaction with an offshore structure (Barrette et al. 1999). Fig. 12 shows the relationship between elastic modulus and flexural strength, and a linear fit to the data gives

$$E = 549.8\sigma_f \tag{15}$$

with $R^2 = 0.268$. The data were divided into three groups of ice temperature. For each group, the test results are around the fitted line. This means that ice temperature does not affect E/σ_f. The average of E/σ_f is 549.8 for sea ice in the Bohai Sea.

The ratio of E/σ_f is 4,239.9 from Timco and O'Brien (1994) for "cold" ice at a temperature of $-20\,°C$, and 1,859.7 from Blanchet (1997) for "warm" ice at $-2\,°C$. Both are higher than that of this study. The simple beam method used here resulted in a higher flexural strength value than the cantilever beam test method because of the weakening of the stress concentration at the root of the cantilever. For the centrifuge tests of Barrette et al. (1999), the ratios are 1,164.7, 605.9, and 299.4 under

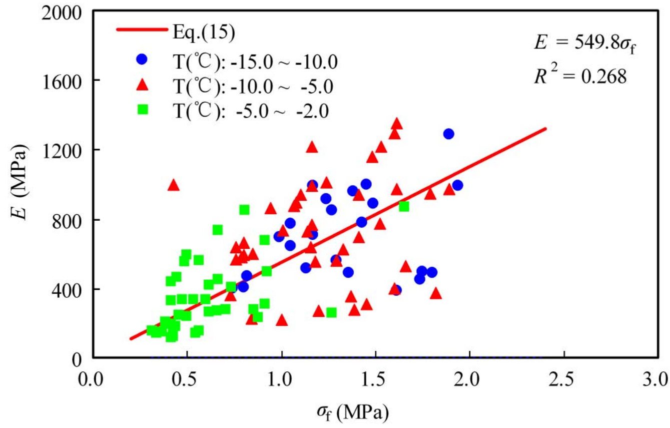


Fig. 12. Elastic modulus versus flexural strength

the acceleration of 25, 12.5, and 1.0 g, respectively. The confining stress induced by the acceleration can increase the elastic modulus and the ratio of E/σ_f. Thus, it indicates that the ratio of E/σ_f is affected by the test method, and the confining stress in centrifuge tests.

Conclusions

The mechanical and physical properties of sea ice are the basic parameters for structural design and sea ice dynamic characteristics in ice-covered regions. During the two consecutive winters of 2008–2010, the writers conducted field tests and laboratory experiments on the elastic modulus and flexural strength of sea ice samples collected from nine sites in the Bohai Sea. The influence of brine volume, ice temperature, and stress rate were analyzed. Both the elastic modulus and flexural strength increase with the decrease of brine volume, and can be described as an exponential function of the square root of brine volume. For the influence of stress rate, the elastic modulus is independent of stress rate, whereas the flexural strength is a linear function of stress rate and increases with the increase in stress rate. The flexural strength of sea ice can be simulated as a two-parameter exponential equation with the consideration of both brine volume and stress rate. The parameters in the equations were determined with the experimental data.

Acknowledgments

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