Article
Method for Testing Shear and Tensile Strengths of Freshwater/Seawater Ice

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Abstract: When amphibious aircraft, ships, and other equipment perform tasks on the water, especially in winter or in low-temperature environments such as high latitudes, high altitudes, and polar regions, they will inevitably encounter icing problems which can adversely affect the safety and performance of these devices. In order to study the mechanical properties of freshwater and seawater ice, this paper tests and analyzes the tensile and shear strengths of static ice and proposes the test principle of shear and tensile strengths of static ice. It then designs and builds the corresponding test equipment, prepares the freshwater and seawater ice samples, and completes the tests. Experiments yield the shear and tensile strengths of freshwater and different seawater samples at various temperatures, and the temperature–strength curves are then drawn. The findings can provide technical support and valuable reference for anti-icing and de-icing design of water vehicles in low-temperature and hostile ocean environments.

Keywords: freshwater ice; seawater ice; shear strength test; tensile strength test

1. Introduction

Ice can cause great damage in aircraft, transport, electricity, and other industries [1–3]. Icing on the surface of amphibious aircraft, ships, and other water vehicles is harmful [4]. During the taking off and landing of amphibious aircraft, water often adheres to the fuselage and other parts, as shown in the landing gear cabin in Figure 1. When amphibious aircraft work in a low-temperature environment, ice will gather on the cabin wall, tires, landing gear, and brake pads. The ice can affect the function and performance of aircraft components, including movable parts such as hatches. The ice on the surface of brake pads and tires can affect the operability and safety of an aircraft during its landing, which then reduces the maneuverability and jeopardizes the safety of the aircraft.

Figure 1. Takeoff of amphibious plane on water.
The same problem also occurs on the surface of ships. Because polar sailing ships and offshore platforms need to operate in a low-temperature environment, seawater ice often freezes on their surfaces [5–8]. Freezing ice on the surface of polar sailing ships and offshore platforms can cause many problems: mobile machinery such as cranes on ship surfaces can break down due to ice formation; personnel movement and deck operation can be more difficult and dangerous; the operation of some life support facilities can become riskier. If the hull is covered with a large amount of ice, the excessive weight of the hull can affect the seaworthiness and stability of the ship and bring risks to normal navigation. Icing can cause problems for other vehicles, including helicopters, hovercraft, and wing-in-ground-effect craft.

Currently, there are many anti-icing and de-icing methods for water vehicles, most of which involve chemical, thermal, and mechanical methods, and some of which are still in the development phase [8]. Chemical de-icing and anti-icing methods are widely used in different fields. Anti-/de-icing chemicals include several chlorides, formats, and acetate, namely sodium chloride and calcium chloride, magnesium chloride, calcium and magnesium acetate, potassium acetate, potassium formate, sodium acetate, and sodium formate [9,10]. Disadvantages of chemical de-icing methods include high cost, corrosion, the potential for secondary freezing, residual substances, and environmental pollution [5,11]. Heating methods include applying heat to the inside or outside of a surface by various means, such as wires, heating pipes, hot water, and hot air [12]. Using heat to start a melting process usually consumes a lot of energy, at least 300 kJ/m² [13]. However, in some cases, this is an appropriate approach when other methods are not available. For example, in ships and other applications, hot water is more effective in preventing ice in the short term; even when there is a small amount of ice accumulation, de-icing is essential for operation. In addition, there are ultrasonic de-icing, superhydrophobic coating, and water lubrication coating methods [14–17].

At present, when there is a lot of ice accretion, it is necessary to use chemical, heating, and mechanical de-icing methods to remove the accumulated ice layer, instead of manually stripping the ice from the vehicle surface. To address this problem, studies should examine ice intensity and influencing factors (temperature, freshwater, or seawater) of typical amphibious aircraft and ships.

Ice is a complex structure with various morphologies. Its morphology and structure may be affected by pressure, temperature, composition, and other impurities including air or gas bubbles. The composition of seawater varies enormously around the globe and across different depths [18,19]. Recently, achievements have been made in the measurement of freshwater ice and sea ice. Researchers have found that the existence of an energy sink results in cooler solid particles as compared to the flowing fluid [20]. The flexural strength of ice has been studied in [21]. Researchers have indicated that solid movement influences heat transfer from warm water to the solid, as governed by the definition of a dimensionless parameter [22]. The mechanical behaviors of ice have been studied and methods for measuring the shear strength and tensile strength of ice are summarized in [23].

In a study on shear strength, Frederking and Timco [24] measured the shear strength of granular and discontinuous columnar sea ice. Gupta and Bergstrom [25] presented a model for the compressive failure of polycrystalline ice via the process of shear faulting and carried out relevant tests. The shear failure of freeze–thaw bonds in salt ice was studied by researchers [26–29]. Researchers carried out the direct shear test, unconfined single-sided shear test, double-sided shear test, and confined single-sided shear test to measure the shear strength of ice [30,31]. Also, researchers designed a test rig and studied the influence of strain rate on shear adhesion strength of impact ice [32,33].

Some studies have measured the tensile strength of ice. For example, Currier and Schulson [34] studied the effect of grain size on tensile strength based on dislocation mechanics and linear elastic fracture mechanics; Mohamed and Farzaneh [35] examined the tensile strength of atmospheric icing; Dempsey et al. [36] and Petrovic [37] studied the
tensile strength and influencing factors of ice; Dykins [38] investigated the strength and influencing factors of naturally formed sea ice; Zhang [39] measured the tensile strength, fracture toughness, and other mechanical properties of ice by Brazilian disc splitting. Most of the above studies intended to examine the columnar ice formed in the natural environment; however, little research has focused on static freshwater and seawater ice with small grains and without obvious axial directions.

There are two common types of ice formation: one is static icing, i.e., slow icing of stationary water droplets or water layers; the other is dynamic icing, i.e., water droplets hitting the substrate surface in a dynamic manner and then icing. This research investigates static icing of typical freshwater and seawater at a low temperature; the ice in this paper is frozen under static conditions. It proposes a test principle for shear and tensile strengths of freshwater and seawater ice, based on the mechanical model of typical shear tests and disc splitting tests. The corresponding test device is designed and built, the ice sample is prepared, and the test is conducted. This study also puts forward a method for testing shear and tensile strengths of freshwater and seawater icing, providing technical support for the anti-icing and de-icing design of amphibious aircrafts, ships, and other water vehicles.

2. Methods

To investigate the impact of icing problems on amphibious aircrafts, polar ships, and other icing-prone equipment, it is necessary to test and analyze the mechanical properties of ice through tests and then formulate reasonable anti-icing methods. In this section, shear strength tests of seawater and freshwater freezing in a series of low-temperature environments were carried out, and the Brazilian disc splitting test method was used to explore the tensile strength of freshwater ice and seawater ice.

2.1. Shear Strength Test

2.1.1. Shear Strength Test Principle and Design

Shear strength refers to the maximum shear stress that resists the failure of the shear force when the material is subjected to shear force. The shear strength test of this study aims at investigating the shear strength of freshwater and seawater ice in a low-temperature environment [25].

Ice has complex material properties, and the shear strength of ice is affected by the ice crystal structure, salinity, temperature, loading directions, and other factors, showing different failure modes. The pure shear strength of ice is difficult to be measured directly through experiments, so there is no reliable and convenient method or relevant test standard for measuring the shear strength of ice. So far, the shear strength of ice has been mostly measured by metal or rock shear test methods, including the unconfined single-sided shear test, double-sided shear test, and confined single-sided shear test. Due to the low tensile strength of ice, the ice sample can be damaged in advance if tensile stress occurs in the test, resulting in a large test error. Therefore, it is necessary to reduce or eliminate the tensile stress of the ice sample as much as possible. In the test of this study, the confined single-sided shear test method is used to avoid the tensile stress of ice specimens. The shear force is shown in Figure 2, where \( h \) is the thickness of the sample, and \( b \) is the width of the sample. At the upper and lower planes of the ice specimen, half of the specimen area is loaded. The testing machine applied load to the upper and lower planes of the ice specimen through indenters is shown in Figure 3a. At this time, the ice layer on the shear plane runs through the connection plane between the upper and lower loading areas in the middle boundary line of the specimen surface, and is subject to shear force.
The corresponding test method of the shear strength of ice is designed. The ice mold is used to make the water sample freeze to form the ice sample. The ice sample is processed to a suitable shape in the low-temperature chamber to make the ice sample easy to load. The ice sample is put into the loading device, and the temperature of the ice sample is controlled to be the same during the test. The indenter of the testing machine is used to load the loading device at a constant speed, the force and displacement data of the indenter at different times are automatically collected, and the temperature data of the test and sample thickness \( h \) (the width \( b \) of the sample is known) are synchronously measured and recorded. When the freshwater ice and seawater ice samples are sheared, the shear stress reaches its peak value, and the stress value is the shear strength of the ice samples, which can be calculated according to Equation (1) [30]:

\[
\sigma_s = \frac{P_{\text{max}}}{bh}
\]

where \( \sigma_s \) is the shear strength; \( P_{\text{max}} \) is the maximum shear force in ice shear failure; and \( b \) and \( h \) are the width and height of the shear plane, respectively.
2.1.2. Shear Strength Test Equipment and Sample Preparation

To test the shear strength of icing, a confined single-sided shear test device is designed. The device consists of upper and lower indents and side limit sleeves; the indents and sleeves are made of stainless steel.

The internal section size of the side limit sleeve is 50 × 50 mm and the height is 75 mm. During the test, the ice sample is placed between the upper and lower indents in the sleeve. By installing the sleeve, this study avoids the tensile force of the ice sample and ensures the loading direction of the upper and lower indents. The loading area of the upper and lower indents is 50 × 25 mm, and other areas are cut to ensure that the shear plane of the ice sample is perpendicular to the loading plane. The test device is shown in Figure 3.

In the test, the low-temperature environment test chamber is used to provide the low-temperature environment for the freezing of the test piece, as shown in Figure 4a. After the ice sample is frozen, its upper surface is uneven, as shown in Figure 5a. Before the experiment, its surface needs to be cut flat, as shown in Figure 5b, in order to apply the load. The cutting and trimming procedure is completed in the low-temperature operation test chamber, as shown in Figure 4b. When loading, the test uses the low-temperature hygrothermal electronic universal testing machine, as shown in Figure 4c. Three test chambers are calibrated, and the measurement results are the same when the temperature is the same.

![Figure 4. Environment chamber and universal testing machine. (a) Low-temperature environment test chamber. (b) Low-temperature operation test chamber. (c) Low-temperature electronic universal testing machine.](image)

![Figure 5. Cross section of ice sample. (a) Before processing. (b) After processing.](image)

The no-load cooling rate of the low-temperature environment test chamber and low-temperature operation test chamber is ≥2 °C/min, the temperature uniformity is ±0.5 °C, and the temperature deviation is ±0.4 °C. The temperature range of the low-temperature hygrothermal electronic universal testing machine is −70 °C~+150 °C, the control accuracy is ±1 °C, the maximum test force is 10 kN, and the measurement accuracy of the test force is higher than ±1% of the indicated value.
The heat insulation foam box is used to preserve and transfer samples is shown in Figure 6. A salinity meter is used to measure the salinity of the seawater samples, the cold storage cabinet to preserve the seawater, a syringe to prepare ice sample preparation, a mold to make ice, vaseline to seal the mold, and an electric shovel to cut and modify the ice sample.

![Figure 6. Heat insulation foam box.](image)

Pure water is selected for the freshwater test; surface seawater samples taken from Dalian, Qingdao, Fuzhou, and Zhuhai are used as the ice resource. All the seawater samples are filtered in the laboratory, and the insoluble substances in the water sample, such as sand and algae, are removed. The salinity of the filtered water sample is then measured and stored in the low-temperature refrigerator, as shown in Figures 7 and 8.

![Figure 7. Storage of seawater samples.](image)

![Figure 8. Filtration process.](image)
The salinity of the filtered seawater is then measured; the results are shown in Table 1.

**Table 1.** Average salinity of the filtered seawater for shear strength test.

| Seawater   | Dalian | Qingdao | Fuzhou | Zhuhai |
|------------|--------|---------|--------|--------|
| Average salinity | 29.3‰ | 28.1‰ | 26.5‰ | 8.7‰   |

In the experiment, a 3D resin printing mold is used to make ice samples. The internal dimension of the rectangular ice mold for the shear test is 50 mm × 50 mm × 70 mm (L × W × H), as shown in Figure 9.

![Figure 9. The 3D resin printing mold for the shear strength test.](image)

2.1.3. Experimental Procedure of Shear Strength Test

Considering the working environment of amphibious aircraft and polar navigation ships, five low temperatures of −10, −20, −30, −40, and −50 °C are selected for the low-temperature environment test to study the influence of temperature on the ice shear strength. The freezing performance at −15 °C is added to seawater icing tests. Figures 10–12 show the flow chart of the experimental procedure, the ice sample of the shear test in the mold after freezing, and the freshwater ice and seawater ice after shear failure, respectively.

![Figure 10. Flow chart of shear strength test.](image)
As can be seen in Figure 9, the experimental procedure is as follows:

1. Prepare the test, seal the mold and mold base with vaseline, and inject water into the mold to a depth of 60 mm. Then, inject a small amount of water into the heat insulation foam box and freeze the foam box in the corresponding low-temperature environment of the cryogenic test chamber. Install the test device on the test machine, and use the plumb line to calibrate the test device so that the upper and lower indenters are aligned with the side limit sleeve.

2. Put the mold with water into the low-temperature test chamber, adjust the temperature to −10 °C, and leave the mold in the chamber for 24 h.

3. Move the ice into the temperature test chamber by using the heat insulation foam box, and place the ice for 12 h at a given low temperature to ensure the stable temperature of the sample.

4. Take out the ice sample in the low-temperature test chamber, remove the mold, cut off the ice with bubbles, and reshape the ice in the test chamber for low-temperature operation. Then, measure, number, and record the ice sample data according to the test requirements.

5. Transfer the ice sample into the test box for the shear test, with the heat insulation foam box. Push the ice sample into the side limiting sleeve, and hold the ice sample under the indenter. Start the testing machine to make the upper indenter enter the side limit sleeve. When the side limit sleeve moves downward, the reading value of the force sensor should not change.

6. Start the test, load at a constant speed until the specimen presents shear failure and the sensor reading value drops rapidly; then, stop loading.
(7) Reset and record the test data, take out the ice sample record, and clean and arrange the test equipment.

In the seawater ice tensile strength test, when the loading rate is 0.5 mm/min, the seawater ice undergoes plastic deformation, no obvious cracks appear in the ice body, and the sensor reading does not change abruptly. This is because of the ductile–brittle transition characteristics of seawater ice. When loaded at low speed, seawater ice does not show obvious brittleness, so the experiment was carried out at a loading rate of 10 mm/min.

In addition to temperature and other factors, the shear strength of ice is also related to the strain rate [24,27,31]. When the strain rate is low, the failure form of ice is ductile failure, and the ice shows brittle failure form at a high strain rate. There is a ductile–brittle transition between ductile failure and brittle failure [40,41], and the ductile–brittle transition strain rate is also different for different types of ice. In the study of Jia Qing et al. [42], the ductile–brittle transition of freshwater ice occurred in the strain rate range of 1.0 × 10⁻⁴–5.0 × 10⁻⁴ s⁻¹. In this paper, artificial ice was investigated. Under the loading rate of 10 mm/min, brittle failure of ice was observed in the experiment.

The strain rate of the ice specimen during the loading process is as follows [31]:

\[ \varepsilon = \frac{v}{h} \]  

where \( \varepsilon \) is the strain rate, \( v \) is the loading rate, and \( h \) is the thickness of the ice sample.

In the shear test of freshwater ice, the strain rate is 2.6 × 10⁻⁴ s⁻¹ to 2.9 × 10⁻⁴ s⁻¹, and that of seawater ice is 5.2 × 10⁻³ s⁻¹ to 5.8 × 10⁻³ s⁻¹.

2.2. Tensile Strength Test
2.2.1. Tensile Strength Test Principle and Design

The tensile strength of ice is of great significance to the study of the failure mode and mechanism of ice. In the research of ice tensile strength, there is no standard measurement method or accurate measurement results. At present, the tensile strength test of ice usually uses the methods of civil engineering to test the tensile strength of rock materials, such as uniaxial tensile test, Brazilian disk splitting test, square plate axial fracturing test, and axial compression die tensile test [39]. To accurately and conveniently measure the tensile strength of ice, Brazilian disc splitting test is selected as the tensile strength test method to test the static icing of different water samples. The stress of Brazilian disc splitting test is shown in Figure 13.

![Figure 13. Stress condition of Brazilian disc splitting test.](image-url)
In the Brazilian disc splitting test, a group of parallel upper and lower platens are usually set up so that the load-bearing specimen processed into a flat cylinder shape (i.e., a disc) is subjected to the counter pressure of the upper and lower platens. The loaded disk specimen is subjected to a line load on the compression line in contact with the pressing plate, and the compression stress is generated in the diameter direction of the connection line of the compression point. At this time, the tensile stress in the inner part of the disc specimen is perpendicular to the diameter direction of the line of the compression point. After the failure of the specimen due to tensile stress, the maximum load of specimen failure can be obtained. The tensile strength can be determined by Equation (3):

$$\sigma_t = -\frac{2P_t}{\pi Dt}$$  \hspace{1cm} (3)

where $\sigma_t$ is the tensile strength of ice, $P_t$ is the Failure load, $t$ is the thickness of the disk specimen, and $D$ is the diameter of the disk specimen.

According to the analytical solution of elastic mechanics of plane stress, the stress state of a point $T (x, y)$ in the disk and the corresponding internal position of the sample can be solved [43].

$$\sigma_x = \frac{2P}{\pi t} \left( \frac{\sin^2 \theta_1 \cos \theta_1}{r_1} + \frac{\sin^2 \theta_2 \cos \theta_2}{r_2} \right) - \frac{2P}{\pi Dt}$$  \hspace{1cm} (4)

$$\sigma_y = \frac{2P}{\pi t} \left( \frac{\cos^3 \theta_1}{r_1} + \frac{\cos^3 \theta_2}{r_2} \right) - \frac{2P}{\pi Dt}$$  \hspace{1cm} (5)

$$\tau_{xy} = \frac{2P}{\pi t} \left( \frac{\sin \theta_1 \cos^2 \theta_1}{r_1} + \frac{\sin \theta_2 \cos^2 \theta_2}{r_2} \right)$$  \hspace{1cm} (6)

where $\sigma_x$ is stress in the X direction of point $T$ in the disk, $\sigma_y$ is stress in the Y direction of point $T$ in the disk, $\tau_{xy}$ is shear stress at point $T$ in the disk, $P$ is the force of the platen, $\theta_1$ is the angle of the upper platen connection on point $T$, $\theta_2$ is the angle of the lower platen connection on point $T$, $r_1$ is distance between point $T$ and the upper platen, and $r_2$ is distance between point $T$ and the lower platen.

Under the action of the linear load at the upper and lower platens, $r_1 = r_2 = 0.5D$; at the center point of the disc, $\theta_1 = \theta_2 = 0^\circ$. The horizontal tensile stress in the vertical diameter plane and the compressive stress in the horizontal diameter plane are as follows:

$$\sigma_x = -\frac{2P}{\pi Dt}$$  \hspace{1cm} (7)

$$\sigma_y = \frac{6P}{\pi Dt}$$  \hspace{1cm} (8)

The tensile stress at the disc center is one third of the compressive stress, and the tensile strength of ice is generally one sixth to one tenth of the compressive strength. The failure of the disc load test is caused by the fact that the tensile stress of the specimen reaches the tensile strength. We can replace $P$ in Equation (7) with $P_t$ to obtain the calculation equation of tensile strength. This is the basic principle of the Brazilian split test.

In the test, the application of a linear load often leads to the problems of specimen sliding and inaccurate stress. Therefore, in the Brazilian test, the disk specimen can be processed into a parallel upper and lower platform; this platform is located on the symmetrical axial plane perpendicular to the end face of the specimen, and the corresponding angle of the platform $2\alpha$ is the loading angle, as shown in Figure 14.
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**Figure 14.** The condition of the ice with platform.

When the ice plate with platform is used, the width of the disk platform needs to be taken into account in the test results. Thus, the tensile strength should be Equation (3) multiplied by a correction factor $k$, and the analytical equation of the loading angle $k$ related to the platform can be obtained through the analysis of ANSYS [44]:

$$k = \frac{(2\cos^3\alpha + \cos \alpha + \sin \alpha/\alpha)^2}{8(\cos \alpha + \sin \alpha/\alpha)}$$

(9)

where the influence factor $k = 1$ when $\alpha$ is $0^\circ$.

The tensile strength (where minus sign means tensile stress) tested in this test can be expressed as follows:

$$\sigma_t = -k \frac{2P_t}{\pi Dt}$$

(10)

Considering the processing needs and the experience of rock measurement, the thickness–diameter ratio of the test sample is about 0.5.

Based on the test principle shown in Figure 13 and Equation (10), the corresponding test method for ice tensile strength is designed. The water sample is frozen by using an ice mold to form an ice sample. In the low temperature sample chamber, the ice sample is processed to a proper shape to make the ice sample easy to load. The temperature in the test chamber will not change during the test to ensure that the temperature of the ice sample is stable. The platen of the testing machine is used to load at a constant speed. The sensor collects the force and displacement of the platen changing with time, and records the test temperature and other information of the sample before and after the test.
2.2.2. Tensile Strength Test Equipment and Sample Preparation

In order to test the static icing tensile strength of seawater and freshwater, the upper and lower platens are assembled by the self-contained chuck of the environmental testing machine to load the platforms of the disc. The device is shown in Figure 15.

![Brazilian disc splitting test device](image)

**Figure 15.** Brazilian disc splitting test device.

The environmental test chamber, low temperature operation test chamber, universal testing machine, foam insulation box, salinity meter, refrigerator, syringe, and spatula used in this test have been introduced in Section 2.1.2 in relation to the shear strength test.

A 3D resin printing mold is used to make ice sample, as shown in Figure 16. The internal dimension of the disk ice-making mold in the tensile test is 60 mm in diameter and 45 mm in height. The mold is designed with the platform loaded in the split test, and the corresponding angle of the platform is \( \alpha = 15^\circ \) at \( k = 0.9205 \).

![Ice mold for Brazilian disc splitting test](image)

**Figure 16.** Ice mold for Brazilian disc splitting test. (a) Ice sample were frozen and shaped in the ice mold. (b) Ice mold.
2.2.3. Experimental Procedure of Tensile Strength Test

The low temperature tensile strength test is carried out from $-10$ to $-50\, ^\circ\text{C}$. Considering that the freezing point of seawater is usually lower than $0\, ^\circ\text{C}$, the $-15\, ^\circ\text{C}$ test is added to seawater icing tests. The split freshwater ice and seawater ice are shown in Figure 17. The experimental procedure is as follows, with the flow chart being the same as that in Figure 9.

![Figure 16. Ice mold for Brazilian disc splitting test. (a) Ice sample were froze in the ice mold. (b) Ice mold.](image)

![Figure 17. Split ice samples in tensile strength test. (a) Freshwater split ice sample. (b) Seawater split ice sample 1. (c) Seawater split ice sample 2.](image)

1. Seal the mold and mold base with vaseline, inject water into the mold to a depth of 60 mm, inject a small amount of water in the heat insulation foam box, and then freeze the box in the corresponding low-temperature test chamber.

2. Freeze, select, and number the ice samples. The procedure is the same as steps (2)–(4) in Section 2.1.3.

3. Transfer the ice sample into the test box for the disc splitting test, using the heat insulation foam box. Place the ice sample between the upper and lower pressure plates so that the platform of the ice sample is aligned with the pressure plate.

4. Start the testing machine and calibrate the sensor, start the test, load at a constant speed until the specimen presents shear failure and the sensor reading value drops rapidly, and then stop loading.

5. Reset and record the test data, take out the ice sample record, and then clean and arrange the test equipment.

In the tensile strength test, the seawater ice has obvious plastic deformation when loaded at 0.5 mm/min. When loading, there is no obvious crack on the ice, and the sensor cannot read the sudden drop. This is due to the ductile–brittle transition of seawater ice. Under low-speed loading, seawater ice does not show obvious brittleness. The test was carried out at a rate of 10 mm/min.

In the tensile test of freshwater ice, the strain rate is $1.4 \times 10^{-4}\, \text{s}^{-1}$, whilst that of seawater ice is $2.8 \times 10^{-3}\, \text{s}^{-1}$.

3. Results

In the above tests, the shear strength of seawater and freshwater freezing was tested by the confined single-sided shear test method, and the Brazilian disc splitting test method was used to explore the tensile strength of freshwater ice and seawater ice. In this section, the results of the shear strength test and the tensile strength test are shown.

3.1. Results of Shear Strength Test

The typical force time history curve of the shear strength measurement is shown in Figure 18.
In the process of uniform loading, the force gradually increases with time and drops after reaching the peak value. Then, the shear failure occurs on the ice, and the ratio of peak pressure to the shear area is the shear strength of ice in shear failure. In addition, for the shape of the time history curve and the corresponding stress change, the shear failure is a typical brittle failure; that is, when the stress reaches the limit, the failure is completed immediately. When shear failure occurs, the ice crystal at a certain point on the shear surface breaks; that is, after the stress state on the shear surface reaches the failure condition and separation or cracks occur, the cracks instantly propagate along the shear surface and cause the entire destruction of the shear surface.

In the test, under the same loading rate, the freshwater ice sample was damaged in a shorter time than the seawater ice sample. When seawater froze, a cavity containing salt water was formed inside the ice body, which made seawater ice looser than freshwater ice. This was obvious when cutting ice samples, and the brine precipitated on the surface of the ice body could be observed during freezing. When loaded, seawater ice deformed greatly due to its loose structure, while freshwater ice was denser and broke when the deformation was small.

The shear strength measurement of freshwater and seawater icing are shown in Figure 19; the comparison of the seawater and freshwater shear strengths is shown in Figures 20 and 21. The shear strength test data are shown in Tables S1–S5.

Figure 18. Force time history curve. (a) Freshwater, −40 °C, shear strength 1.086 MPa. (b) Qingdao seawater, −30 °C, shear strength 1.003 MPa.

Figure 19. Shear strength results. Shear strengths of (a) freshwater ice, (b) Dalian seawater ice, (c) Qingdao seawater ice, (d) Fuzhou seawater ice, and (e) Zhuhai seawater ice are shown.
Compared with the experimental results of other researchers [24, 27, 29–31], when the temperature is high (−20 °C to 0 °C), the measured shear strength of freshwater ice has a larger range, and the shear strength of seawater ice is lower than that of sea ice in existing studies (about 0.5 MPa, −10 °C); there was not much research data when the temperature is lower than −30 °C.

![Figure 20. Comparison of shear strengths of seawater and freshwater.](image)

Figure 20. Comparison of shear strengths of seawater and freshwater.

![Figure 21. Shear strength and salinity.](image)

Figure 21. Shear strength and salinity.
With the decrease in temperature, the shear strength of the freshwater ice and seawater ice increases first and then decreases. The peak shear strength of the freshwater ice is −30 °C. The shear strength of the freshwater ice increases slowly with the decrease in temperature, but the temperature that reaches the peak is higher than that of seawater ice. The maximum value of the shear strength at −30 °C is 2.438 MPa. When the temperature continues to decrease, the shear strength of the freshwater ice gradually decreases. The shear strength showed a decreasing trend with increasing salinity.

After each seawater ice sample is loaded, the crushed ice cubes are collected and placed into a beaker; then, they are melted, filtered, and measured with a salinity meter. The average salinity of the seawater ice sample in the test is recorded in Table 2.

| Seawater Ice       | Dalian | Qingdao | Fuzhou | Zhuhai |
|--------------------|--------|---------|--------|--------|
| Average salinity   | 17.9‰ | 12.5‰  | 14.1‰ | 7.1‰  |

### 3.2. Results of Tensile Strength Test

In the process of uniform loading, the pressure gradually increases with time and drops after reaching its peak value. When tensile failure occurs, the ice crystal near the center of the disk breaks; that is, after the stress state reaches the failure condition and separation or cracks occur, the cracks instantly expand along the vertical plane connecting the upper and lower steps of the disk and cause the entire splitting of the ice sample.

The measurement results of the tensile strength of freshwater and seawater icing are shown in Figure 22, and a comparison of the average results for tensile strength is shown in Figures 23 and 24. The shear strength test data are shown in Tables S6–S10.

Compared with the experimental results of other researchers [28,34,39,44], when the temperature is high, the measured tensile strength of freshwater ice is not much different (about 0.55 MPa, −10°C), and the tensile strength of seawater ice is lower than that of sea ice studied (about 0.6 MPa, −10 °C); there was not much research data when the temperature is lower than −30 °C.

![Figure 22](image-url). Tensile strength test results. Tensile strengths of (a) freshwater ice, (b) Dalian seawater ice, (c) Qingdao seawater ice, (d) Fuzhou seawater ice, and (e) Zhuhai seawater ice are shown.
The relationship between the shear strength and the temperature of freshwater icing in the test.

In this section, the curve fitting method is used to describe the relationship between the shear strength or tensile strength and the temperature. The reason for the difference in shear strength between different seawater samples is discussed, as well as the main errors in the test.

4.1. Discussion of Shear Strength Test

The relationship between the shear strength and the temperature of freshwater icing is fitted to a quadratic curve.

\[ \tau_{FW}' = -0.00117^2 - 0.0712 + 0.2922 \]  
(11)

For the seawater ice, it is found through experiments that when the temperature of seawater ice is relatively high (higher than \(-20 ^\circ C\)), it is easier for shear failure to occur. However, the shear strength of the seawater ice increases rapidly with the decrease in temperature, reaching or exceeding 1 MPa from \(-30 ^\circ C\) to \(-50 ^\circ C\). When the temperature is not higher than \(-40 ^\circ C\), the shear strength of seawater ice is relatively close to that of freshwater ice. When the temperature is lower than \(-30 ^\circ C\), the shear strength of the seawater ice gradually declines. The freezing point of seawater (with the highest freezing point being \(-5 ^\circ C\)) is lower than that of freshwater (0 °C), so it is more likely to produce shear failure when the temperature is relatively high. The decreasing range of the low-
temperature shear strength of the seawater ice in Dalian is the widest, while that in Fuzhou is not obvious, which may be related to seawater composition and salinity.

Seawater ice is composed of salt-free ice and a cavity containing brine [12]. It is also evident from Figure 22a that salt-free ice has the property that the shear strength increases with decreasing temperature. It is believed that the new ice frozen inside the brine cavity generates large stresses, which leads to microcracks inside the seawater ice. The interaction of these two effects makes the mechanical properties of the ice present extreme values, which are expressed when the temperature decreases. The shear strength of ice increases first; after reaching the extreme, as the temperature decreases, the shear strength gradually decreases.

In the test, an obvious ductile–brittle transition occurs in the shear loading of the seawater ice. When the loading rate is relatively low (less than 0.5 mm/min), the deformation of the seawater ice is mainly plastic deformation. This is because the salt cells and brine bubbles in the seawater ice lead to continuous intergranular slip without obvious brittleness. In this experiment, a loading rate of 10 mm/min was used for the experiment, and the test data in which brittle failure occurred was selected according to the force time history curve of the experimental results.

The maximum strength of Dalian seawater ice measured by the shear test is 1.191 MPa at $-30\,^\circ\text{C}$. The relationship between the shear strength and temperature is obtained by cubic polynomial fitting.

$$
\tau_{DL}' = -0.00002T^3 + 0.0033T^2 + 0.0193T + 0.0279 \quad (12)
$$

The maximum strength of Qingdao sea ice measured by the shear test is 1.094 MPa at $-40\,^\circ\text{C}$. The relationship between the shear strength obtained by polynomial fitting and the change of temperature is as follows:

$$
\tau_{QD}' = 0.00002T^3 + 0.007T^2 - 0.0335T - 0.2769 \quad (13)
$$

The maximum strength of Fuzhou seawater ice measured by the shear test is 1.179 MPa at $-40\,^\circ\text{C}$. The relationship between the shear strength obtained by polynomial fitting and the change of temperature is as follows:

$$
\tau_{FZ}' = 0.00002T^3 + 0.0012T^2 - 0.0128T + 0.0017 \quad (14)
$$

The maximum strength of Zhuhai seawater ice measured by shear test is 1.020 MPa at $-50\,^\circ\text{C}$. The relationship between the shear strength obtained by polynomial fitting and the change of temperature is as follows:

$$
\tau_{FW}' = -0.000006T^3 - 0.0009T^2 - 0.0566T - 0.1798 \quad (15)
$$

The goodness of the fitting curve of the shear test results is shown in Table 3.

**Table 3.** The goodness of fitting curve of the shear strength test. (The closer the value in the table is to 1, the better the corresponding fitting effect. The seawater test results are well fitted while the freshwater test results are not).

| Ice          | Freshwater Ice | Dalian Seawater Ice | Qingdao Seawater Ice | Fuzhou Seawater Ice | Zhuhai Seawater Ice |
|--------------|----------------|---------------------|----------------------|---------------------|---------------------|
| R2           | 0.1625         | 0.9530              | 0.8776               | 0.9566              | 0.8827              |

The freshwater test results are relatively scattered, and the fitting effect is not desirable. However, the seawater test results are well fitted; there are fewer samples from sea water, and its R2 results are smaller than those from fresh water.
4.2. Discussion of Tensile Strength Test

In the tensile strength test of ice, the tensile strength of the freshwater ice increases gradually with the decrease of temperature, and the tensile strength of the seawater ice reaches its peak at about −30 °C or −40 °C.

The peak value of the freshwater ice tensile strength at −50 °C is 1.325 MPa. The relationship between freshwater tensile strength and temperature obtained by linear fitting is as follows:

\[ \sigma_{FW} = -0.0100T + 0.4340 \]  

(16)

The maximum tensile strength value of Dalian seawater ice appears at −40°C. The measured maximum tensile strength is 0.549 MPa, and the relationship between the tensile strength obtained by the cubic polynomial fitting and the temperature change is

\[ \sigma_{DL} = 0.00003T^3 + 0.0023T^2 + 0.0334T + 0.1925 \]  

(17)

The maximum tensile strength value of Qingdao seawater ice appears at −40°C. The measured maximum tensile strength is 0.606 MPa, and the relationship between the tensile strength obtained by the cubic polynomial fitting and the temperature change is

\[ \sigma_{QD} = 0.00003T^3 + 0.002T^2 + 0.0312T + 0.2208 \]  

(18)

The maximum tensile strength value of Fuzhou seawater ice appears at −40°C. The measured maximum tensile strength is 0.634 MPa, and the relationship between the tensile strength obtained by the cubic polynomial fitting and the temperature change is

\[ \sigma_{FZ} = 0.00003T^3 + 0.002T^2 + 0.0298T + 0.2062 \]  

(19)

The maximum tensile strength value of Zhuhai seawater ice appears at −30°C. The measured maximum tensile strength is 0.576 MPa, and the relationship between the tensile strength obtained by the cubic polynomial fitting and the temperature change is

\[ \sigma_{ZH} = -0.00003T^3 - 0.0028T^2 - 0.0946T - 0.5297 \]  

(20)

The ice experiments of the four kinds of seawater show that tensile failure occurs more easily in ice when the temperature is relatively high (above −20 °C). This is because the freezing point of seawater is relatively low. At this time, there is still unfrozen brine inside the seawater ice sample, resulting in its tensile strength being lower. From −30 °C to −10 °C, the tensile strength of the seawater ice increases rapidly with the decrease in temperature. The tensile strength of seawater ice in Zhuhai reaches its peak at about −30 °C, and the tensile strength of seawater ice in Dalian, Qingdao, and Fuzhou reaches its peak at around −40 °C, and then slows down or declines as the temperature continues to drop. The tensile strengths of the seawater ice in Dalian, Qingdao, and Fuzhou are close to each other. The tensile strength of the seawater ice in Zhuhai is larger than that of other seawater ice at a higher temperature, and these strengths gradually become consistent when the temperature drops to −50 °C, which may be related to seawater ice in Zhuhai having the lowest salinity.

For freshwater ice, as the temperature decreases, the mechanical properties of ice crystals will gradually increase, thereby increasing the shear strength. For seawater ice, similar to Section 4.1, it is believed that the interaction of the salt-free ice and cavity containing brine causes the tensile strength of ice to increase to the extreme first, and then as the temperature decreases, the tensile strength gradually decreases.

The goodness of the fitting curve of Brazilian disc splitting test results is shown in Table 4. The freshwater test results are relatively scattered, and the fitting effect is not desirable; nevertheless, the seawater test results are well fitted, there are fewer samples from sea water, and its R2 results are smaller than those from fresh water.
The goodness of fitting curve of tensile strength test. (How close the values in the table are
to 1 determines the curve fit accuracy. The seawater test results are well fitted while the freshwater
test results are not).

| Ice       | Freshwater Ice | Dalian Seawater Ice | Qingdao Seawater Ice | Fuzhou Seawater Ice | Zhuhai Seawater Ice |
|-----------|----------------|---------------------|----------------------|---------------------|---------------------|
| R²        | 0.4263         | 0.9598              | 0.9499               | 0.879               | 0.8109              |

The main errors in the shear strength and tensile strength test are as follows:

1. The measurement error of the tension sensor is 1% of the indicated value; the data ac-
   quisition instrument has data truncation errors and signal transmission has hysteresis.
2. In the process of ice making, strict single-sided heat transfer is not realized, which is
   controlled by using resin with low thermal conductivity (0.08 W/k).
3. The quality of the ice mold and ice has a great influence on the measurement results.
   After the ice is frozen, the ice sample with clear crystals and without cracks is se-
   lected, and the irregular part of the ice sample is removed and controlled by cutting
   and trimming.

5. Conclusions

This study designs and implements the test of shear and tensile strengths of freshwater
and seawater ice based on the mechanical model of typical shear and disc splitting tests.
It proposes the test principle and method, and analyzes the influence of temperature,
freshwater, and seawater from different regions on the shear and tensile strengths of
static ice.

1. The confined single-sided shear test and Brazilian disc splitting test of freshwater and
   seawater icing are designed and carried out in a low-temperature environment (from
   −10 °C to −50 °C).
2. The relationship between the shear strength of freshwater and seawater ice with the
   temperature change is studied. After the relationship of the shear strength of different
   water sources with the change of time is obtained, the appropriate lines are selected
   for fitting. It is found that the shear strength of freshwater and seawater ice increases
   at first and then decreases with the decrease in temperature. The strength of seawater
   ice is lower than that of freshwater ice at around 0 °C, but gradually approaches that
   of freshwater ice when the temperature decreases.
3. The relationship between the tensile strength of freshwater and seawater ice with the
   temperature change is also studied. The appropriate line is selected for fitting after
   the relationship of the tensile strength of different water sources ice with the change
   of time is obtained. It is found that with the decrease in temperature, the tensile strength
   of freshwater ice has a linear relationship with temperature.
4. In the anti-/de-icing design, since the increase in temperature will reduce the shear
   strength and tensile strength of the ice, it is possible to adopt local heating methods at
   the locations where the ice is easy to freeze to reduce the difficulty of de-icing.

The findings of this study can provide technical support for anti-icing and de-icing
designs of amphibious aircraft, ships, and other water vehicles.

Supplementary Materials: The following supporting information can be downloaded at: https://
//www.mdpi.com/article/10.3390/w14091363/s1, Table S1: Freshwater Shear Test Data; Table S2:
Dalian Seawater Shear Test Data; Table S3: Qingdao Seawater Shear Test Data; Table S4: Fuzhou
Seawater Shear Test Data; Table S5: Zhuhai Seawater Shear Test Data; Table S6: Freshwater Tensile
Test Data; Table S7: Dalian Seawater Tensile Test Data; Table S8: Qingdao Seawater Tensile Test Data;
Table S9: Fuzhou Seawater Tensile Test Data; Table S10: Zhuhai Seawater Tensile Test Data.

Author Contributions: Conceptualization, Y.Z. (Yongjie Zhang) and Y.Z. (Yunhui Zhang); method-
ology, Y.Z. (Yongjie Zhang) and Y.Z. (Yunhui Zhang); software, Y.Z. (Yunhui Zhang); validation,
Y.Z. (Yunhui Zhang) and R.G.; formal analysis, Y.Z. (Yongjie Zhang), Y.Z. (Yunhui Zhang) and R.G.;
investigation, Y.Z. (Yunhui Zhang) and R.G.; resources, R.G. and B.C.; data curation, R.G. and B.C.;
writing—original draft preparation, Y.Z. (Yongjie Zhang), Y.Z. (Yunhui Zhang) and B.C.; writing—
review and editing, Y.Z. (Yongjie Zhang), Y.Z. (Yunhui Zhang) and B.C.; visualization, Y.Z. (Yunhui
Zhang), R.G. and B.C.; supervision, Y.Z. (Yongjie Zhang); project administration, Y.Z. (Yongjie Zhang);
funding acquisition, Y.Z. (Yongjie Zhang). All authors have read and agreed to the published version
of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China (Grant
Nos. 11972301, 11201375, 11972300), the Natural Science Foundation of Shaanxi Province (Grant No.
2018Q1071), State Key Laboratory of Structural Analysis for Industrial Equipment (China) (Grant
No. GZ18107) and the Fundamental Research Funds for the Central Universities of China (Grant No.
G2019KY05203).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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