Experimental Study on Mechanical Properties of Ice

Wenyuan Meng ,Yingkui Guo
NCWU, Zhengzhou, Henan, 450011

***Abstract*—In order to solve the problem of determining the value of mechanical parameters of ice in the prevention and cure of ice flood disaster, on the basis of experimental methods of classical mechanics, through improving the test equipment and controlling test conditions ,we obtain the strength, deformation and modulus of elasticity of ice under different temperature(-5℃、-15℃、-25℃、-30℃、-35℃、-40℃)and different loading strain rate(0.05KN/S、0.1KN/S、0.3KN/S 、 0.5KN/S 、 0.8KN/S).Through analyzing and comparing ice damage characteristics and stress-strain curves under different conditions , we obtain mechanical parameters and material property of ice, and thus supply reference data when researching the prevention and cure of ice flood disaster, ice blasting and ice numerical simulation.**

Keywords-ice; mechanical property; experiment

I. INTRODUCTION

There are ice jam, ice dam Etc. easily happening in Chinese northern rivers , winter and spring. In these ice flood disasters ,there are several effect from drift ice impacting the piers and dams, frost -heaving force of ice sheet acting on bridges and dams, which seriously influence the structure in the water to operate safely and people along the river to live normally. To prevent and control the ice flood disaster ,it's of realistic significance and practical value to develop the research on the prevention and cure of ice flood disaster and mechanical property of ice.

Because of the specificity of ice, there are little research on ice mechanical property at home and abroad currently. Professor Li Zhijun from Dalian University of Technology mainly develop the research on physical and mechanical property of sea ice; Professor Yu Tianlai from Northeast Forestry University and Professor Meng Wenyuan from North China University of water conservancy and hydroelectric power mainly develop mechanical property of river ice and the prevention and cure of ice flood disaster. There is no unified standard value of mechanical parameters of ice at present due to the lack of the standard of ice mechanics test and special test equipment. Through the compression test and splitting tensile test in this paper, we obtain the strength, deformation and modulus of elasticity of ice under different temperature and different loading strain rate and their relationship, which lay the foundation for the subsequent study on the ice numerical simulation ,ice blasting and the prevention and cure of ice flood disaster .

II. THE GEOMETRICAL CHARACTERISTICS OF THE CURVE OF ICE UNDER UNIAXIAL COMPRESSION

In the process of test, stress-strain curve of ice shows some certain features in the shape. So we chose the typical ones to analyze its feature. The results are represented in figure 1 below: 1)there is a obvious straight line in the elastic stage. 2) The brittle characteristics are evident. Ice crashes and abates directly when the loading reaches the ultimate strength.

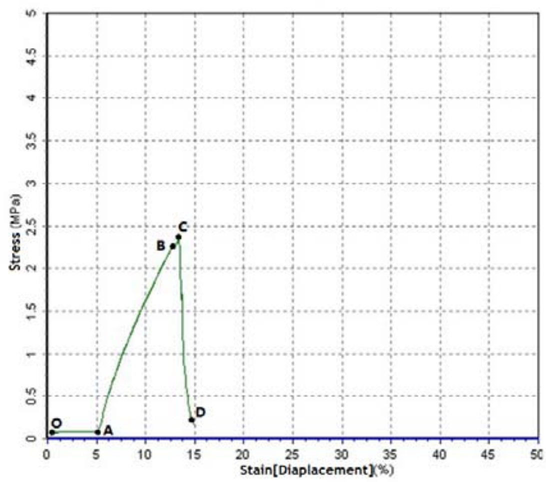

Figure 1. Typical stress-stain curve of ice

In Figure 1, the O-A stages shows a straight line nearly because the instrument probe doesn't contact the ice specimen completely and the surface of ice melts when the probe contact the specimen. So a small force result in larger deformation. In the A-B stages ,there are few visible cracks in the specimen, but the cracks develop continuously. The tangent slope of the curve decreases continuously. It means that the necessary force reduces gradually if the same deformation is produced. In the B-C stages ,bubbles and cracks in the sample feed through and form the failure surface and the internal structure of ice specimen adjusts. After Point C, the curve goes into the decline stage and thus the peak stress is the compressive strength of ice specimen. In the C-D stages, the ice specimen crashes and abates with the cracks expanding continuously. The curve declines very steeply in this stage and thus the ice shows embrittlement. Finally the strength of ice specimen gets close to zero.

III. ANALYSIS OF THE TEST DATA

A. *Compression Test*

The compression strength and the modulus of elasticity of ice are main parameters of study on blasting in water under the ice. If these parameters are obtained, they will provide the reference data for engineering practice and numerical simulation. Besides, the uniaxial compression test without lateral restriction is the basic method for studying the basic characteristics of natural ice and ice mechanical properties. Under the action of force, ice produces local or internal cracks. With the force increasing, the crack extends and expands. Finally the ice crashes and abates. The damage that the ice suffers exists all along. So we usually determine the maximum resistance in accordance with the strength. And we don't consider the damage of internal microstructure of ice but take the ultimate stress as the uniaxial compression strength of ice through the test. The uniaxial compression strength should be calculated according to the following formula.

$$f_{cp} = \frac{F}{A} \tag{1}$$

Where, f_{cp} is the uniaxial compression strength, F is maximum load to a rupture of test specimen and A is the bearing area of test specimen.

Experimental data is shown in Table I.

TABLE I. UNIAXIAL COMPRESSION STRENGTH UNDER DIFFERENT TEMPERATURE AND DIFFERENT LOADING STRAIN RATE

Loading strain rate (KN/s)	Uniaxial compression strength (Mpa)					
	-5°C	-15°C	-25°C	-30°C	-35°C	-40°C
0.05	3.0191	2.6947	3.4331	2.9437	6.4338	4.4551
0.1	3.3699	2.9004	3.5968	3.4830	5.1750	4.4886
0.3	2.7416	2.9867	2.9565	4.0941	6.8850	5.1350
0.5	3.5045	3.1564	3.5824	4.9345	6.0676	4.0158
0.8	3.4668	4.0661	3.7903	3.7776	4.7471	3.1213

The relationship between the uniaxial compression strength and temperature , loading strain rate are shown in Figure 2, Figure 3.

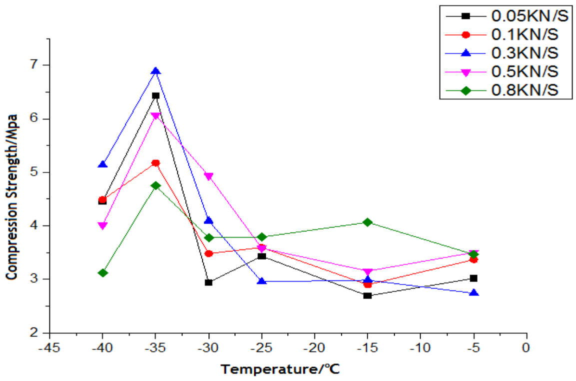

Figure 2. Relationship between the uniaxial compression strength and temperature

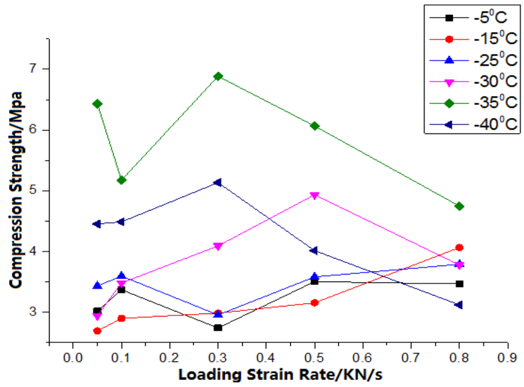

Figure 3. Relationship between the uniaxial compression strength and loading strain rate

On the whole, when the loading strain rate is determined, the compression strength increases with the temperature decreasing with a certain range. The strength goes on to decrease till it maximizes. And then the compression strength shows a downward trend. The loading strain rate has a less obvious effect on the compression strength. When temperature is determined, the compression strength of ice at -30 degrees Celsius increases with loading strain rate increasing below the loading rate 0.5 KN/S and the compression strength of ice at -40 degrees Celsius increases with loading strain rate increasing below the loading rate 0.3 KN/S. The compressive strength reaches the maximum at the loading rate 0.5 KN/S and 0.3 KN/S, respectively. The ice at -30 degrees Celsius,-35 degrees Celsius and -40 degrees Celsius has the maximum compressive strength with the change of the loading rate. And the compressive strength of ice decreases instead after reaching the maximum. The compression strength of ice at -5 degrees Celsius,-15 degrees Celsius and -25 degrees Celsius increases with loading strain rate increasing.

From the data in the table, the compression strength of ice at -35 degrees Celsius reaches the maximum 6.8850 MPa at the loading strain rate 0.3 KN/S.

B. *The splitting Tensile Test*

There are many experimental measurement method of studying on the tensile strength of ice at present. According to different stress conditions of the ice specimen, there are mainly three types of methods as follow: direct tensile test, splitting tensile test and bending test. Among them, the splitting test is simple and practicable. So the splitting tensile strength has already been widely used in engineering currently. And we will infer the axis tensile strength by the splitting tensile strength. The formula for computing the splitting tensile strength for cylindrical specimens is as follows,

$$f_t = \frac{2F}{\pi ld} \quad (2)$$

Where, F is the breaking load of the specimen, l is the height of the specimen and d is the diameter of the cylinder. The formula is commonly used for the moment. The results are shown in Table II.

TABLE II. TENSILE STRENGTH UNDER DIFFERENT TEMPERATURE AND DIFFERENT LOADING STRAIN RATE

Loading strain rate (KN/s)	Tensile strength(MPa)					
	-5^{0}C	-15^{0}C	-25^{0}C	-30^{0}C	-35^{0}C	-40^{0}C
0.05	1.3761	1.4227	1.8724	1.4747	2.0271	1.7800
0.1	2.7064	2.7022	2.3595	2.68662	2.2136	2.3047
0.3	2.433	2.9282	2.2206	2.73631	2.8717	3.3070
0.5	2.7868	2.1547	2.1988	2.56051	2.7228	2.2333
0.8	1.568	1.7063	2.5146	2.4129	2.8839	2.5888

The relationship between the tensile strength and temperature , loading strain rate are shown in Figure 4, Figure 5.

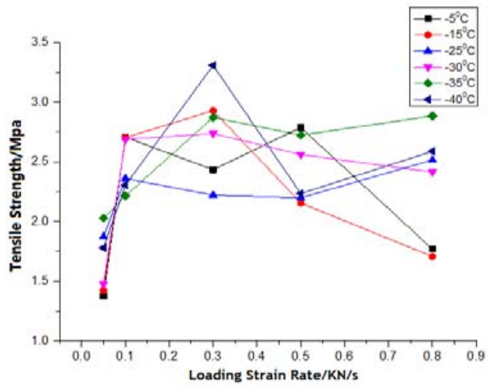

Figure 4. Relationship between the tensile strength and loading strain rate

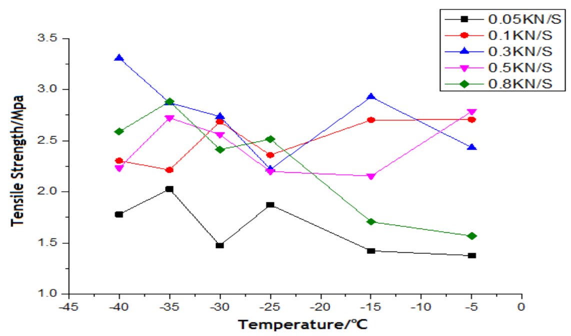

Figure 5. Relationship between the tensile strength and temperature

When the loading rate is determined, the trend that the tensile strength of ice changes with temperature isn't obvious. But there is a maximum value. When the temperature is determined, the trend that the tensile strength of ice changes with the loading rate isn't clear , too. On the whole, the tensile strength of ice shows a similar variation with the loading rate. The tensile strength increases a little with the loading rate raising. The tensile strength of ice reaches the maximum at some loading rate. And then the tensile strength decreases with the loading rate continuing to go up. The tensile strength of ice reaches the maximum 3.3070 MPa at -40 degrees Celsius and the loading strain rate 0.3 KN/S.

C. The Elastic Modulus of River Ice

The elastic modulus of river ice is one of basic parameters for the simulation and analysis of blasting in water under the ice. But there are little domestic study on the elastic modulus of river ice, and we don't understand the regulation very comprehensively. So we can only infer the elastic modulus of river ice with the uniaxial compression strength. In the initial stage when the ice is pressed evenly, the upper press head doesn't full contact the ice specimen because error exists during the process of producing the ice specimen and the upper surface of ice isn't smooth enough. The Elastic properties isn't shown obvious. So we study on the linear increasing phase of the stress-strain curve. The compression elastic modulus should be calculated according to the following formula (3).

$$E = \frac{4l\Delta F}{\pi d^2 \Delta l} \quad (3)$$

Where, l is the height of the specimen , d is the diameter of the cylinder, ΔF is the variation of load , Δl is the average of deformation of both sides of the ice specimen.The results are shown in Table III.

TABLE III. THE ELASTIC MODULUS OF ICE UNDER DIFFERENT TEMPERATURE AND DIFFERENT LOADING STRAIN RATE

Loading strain rate (KN/s)	Elastic modulus(GPa)					
	-5^{0}C	-15^{0}C	-25^{0}C	-30^{0}C	-35^{0}C	-40^{0}C
0.05	0.4680	0.5074	0.5314	0.5988	0.6411	0.5708
0.1	0.5208	0.56746	0.6534	0.7035	0.7383	0.6043
0.3	0.6616	0.74092	0.6913	0.7319	0.7940	0.6823
0.5	0.5801	0.5355	0.5916	0.7350	0.8353	0.5130
0.8	0.4416	0.5076	0.5296	0.5724	0.6888	0.4873

The relationship between the elastic modulus of ice and temperature, loading strain rate are shown in Figure 6, Figure 7.

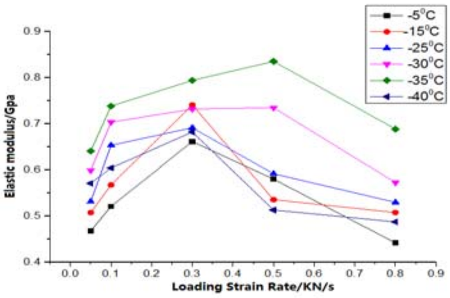

Figure 6. Relationship between the elastic modulus and loading strain rate

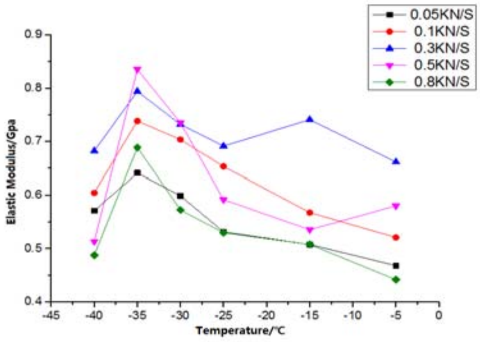

Figure 7. Relationship between the elastic modulus and temperature

From the data in the table, in the range of 0 degrees to -35 degrees Celsius and at the same strain rate, the compression elastic modulus increases with temperature decreasing and reaches the maximum at about -35 degrees Celsius. In the case of the same temperature, the compression elastic modulus changes with the loading rate and has the extreme point, when the loading rates are different, however. The compression elastic modulus of ice at -5,-15 and -25 degrees Celsius increases with the loading strain rate increasing under the loading strain rate 0.3 KN/s. And the compression elastic modulus decreases with the loading rate increasing over the loading strain rate 0.3 KN/s. Similarly, the compression elastic modulus of ice at -30 and -35 degrees Celsius increases with the loading strain rate increasing under the loading strain rate 0.5 KN/s. And the compression elastic modulus decreases with the loading rate raising over the loading strain rate 0.5 KN/s. The compression elastic modulus of ice reaches the maximum 0.8353 GPa at -35 degrees Celsius and the loading strain rate 0.5 KN/s. And the minimum 0.4680 GPa is reached at -5 degrees Celsius and the loading strain rate 0.05 KN/s.

D. The Plasticity Characteristics of Ice

During the process of experiment, we put the ice specimen at -25 degrees Celsius in the environment of room temperature 3 degrees Celsius for 20 minutes. And then we go on the test with the specimen. The results are shown in Figure 8, Figure 9.

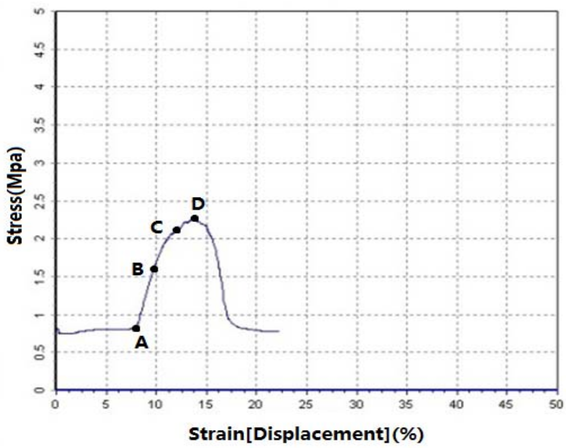

Figure 8. Stress-strain curve at the loading rate 0.3 KN/s

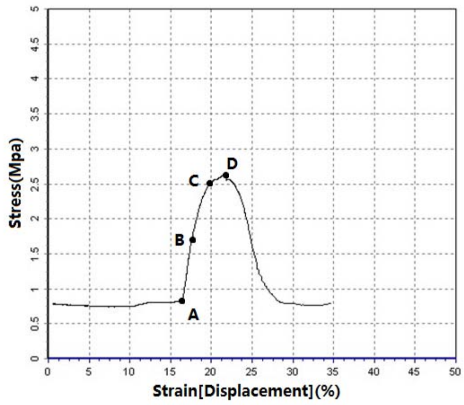

Figure 9. Stress-strain curve at the loading rate 0.8 KN/s

In the A-B stages, the stress strain curve is horizontal straight line nearly because the micro cracks in the ice specimen have no obvious development .In the B-C stages, the cracks in the ice specimen extend gradually and the structure of materials changes. The tangent slope of curve decreases constantly. In the C-D stages, the cracks in the ice specimen expand continuously. After Point D, the curve starts to decline and the curvature gets smaller and smaller. The strength of ice sample decreases but there is some residual strength till the end. The whole process full shows the plasticity characteristics of ice.

IV. CONCLUSION

Main conclusions are as follows.

(1)When the loading strain rate is determined, the compression strength of ice increases with the temperature decreasing with a certain range. The compression strength of ice at -35 degrees Celsius reaches the maximum. And then the compression strength shows a downward trend with temperature decreasing sequentially.

(2)The compression strength of ice at certain temperature (-5 degrees Celsius,-15 degrees Celsius and -25 degrees Celsius) increases with loading strain rate increasing.

(3)Ice belongs to brittle materials, but it presents plasticity characteristics under certain conditions.

(4)In the range of 0 degrees to -35 degrees Celsius and at the same strain rate, the compression elastic modulus of ice increases with temperature decreasing and reaches the maximum at about -35 degrees Celsius.

(5)At the same temperature and loading strain rate, value of the compression strength of ice equals to twice as the tensile strength approximately.

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