Flexural strength of atmospheric ice

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***Abstract*— Bending strength of atmospheric ice accumulated in a closed loop wind tunnel at temperatures -6 °C, -10 °C and -20 °C with a liquid water content of 2.5 g/m^3 was examined at different strain rates. More than 120 tests were conducted to measure the flexural strength of the ice. Ice samples accumulated at each temperature level were tested at the accumulation temperature, but the ice accumulated at -10 °C was also tested at -3 and -20 °C. According to the results of these tests, flexural strength of atmospheric ice depends on test temperature, at low strain rates. At higher strain rates, however, the spread in bending strength for the different temperatures diminishes. For ice accumulated at -20 °C the presence of cavities reduces its bending strength at higher strain rates. The flexural strength of atmospheric ice accumulated at -10 °C has been found to be greater than that of ice accumulated at -6 °C and -20 °C.**

I. INTRODUCTION

Accretion of atmospheric ice on power transmission lines may cause considerable damage to power networks in cold climate regions. Removing the atmospheric ice from network equipment, particularly cables and conductors has drawn much attention lately and consequently, many studies on ice adhesion on substrates, ice shedding and its effects on power network elements have been carried out. Studies on atmospheric icing require knowledge on the mechanical properties of the ice under various temperatures and loading conditions. For example, knowing the behavior of atmospheric ice under bending stress is useful for de-icing studies (e.g. Kalman *et al.*, 2007) and for developing models of ice shedding.

The present investigation is part of a larger study on the measurement of the mechanical properties (compressive strength [8], flexural strength, etc.) of atmospheric ice, yet to be published.

One of the few studies on the mechanical properties of atmospheric ice is the research of Druez *et al*. (1986) on the compressive strength of ice. In their study, ice accumulated at various air temperatures and air speeds was tested at the same temperature as it had been accumulated. They set the liquid water content of air (LWC) at 0.4 and 0.8 g/m^3 and the droplet diameter for these two values of LWC was set at 20 μm and 40 μm, respectively.

In contrast to the few existing studies on atmospheric ice, the flexural strength of other types of ice has been studied by many investigators (e.g. Timco and Frederking, 1982; Frederking and Svec ,1985; Dempsey *et al.*,1989; Gow and Ueda ,1988). Lack of comprehensive information about the strength and mechanical properties of atmospheric ice under various loading conditions led to the present study. In this paper, the flexural strength of atmospheric ice for various accumulation temperatures and strain rates is investigated.

II. TESTS CONDITIONS

Atmospheric ice and its structure can be influenced by the meteorological conditions prevalent during its formation, such as wind velocity, liquid water content of air, mean volume droplet diameter and temperature. Furthermore, the mechanical properties of atmospheric ice are dependent on temperature, load rate, type and its structure. Therefore, the most important aspect in this investigation is selecting the experimental conditions for the ice accumulation and ice tests, which is discussed in the following paragraphs.

A. Temperature

Normally atmospheric icing occurs at temperatures ranging between -6 °C and -20°C, as was acknowledged by other investigators (e.g. Eskandarian, 2005; Mousavi, 2003). Since a typical wintertime temperature in Quebec is -10°C, most of the tests in this study were carried out at this temperature. However, to study the temperature dependence of the mechanical behavior of atmospheric ice some experiments were done at -3 °C and -20 °C, which fall within the typical range of temperatures for Quebec winters.

B. Loading rate

Previous investigations (e.g Hawkes and Mellor, 1972; Schulson and Canon, 1984; Schwarz *et al*.,1981; Wu and Niu, 1995) have shown an appreciable dependence of ice strength on strain rate. Generally, three domains of deformation can be identified in stress-strain rate graphs. These domains for ice tested at -10 °C are distinguished as ductile (at strain rates less than $10^{-4}s^{-1}$ for compression and less than 10^{-7} s^{-1} for tension), brittle (at strain rates more than $10^{-2}s^{-1}$ for compression and more than $10^{-6}s^{-1}$ for tension) and transition (between ductile and brittle) regimes.

The phenomenon of ice shedding usually occurs in the transitional and brittle domains. Furthermore, strain rate in the case of natural ice shedding is not larger than $10^{-2}s^{-1}$. Hence in this study the loads were applied at strain rates ranging between 3×10^{-5} and $3\times10^{-2}s^{-1}$.

C. Ice accumulation conditions

The ice accumulation conditions for this study were created in the CIGELE atmospheric icing research wind tunnel which is a closed-loop (air-recirculated) low-speed icing wind tunnel. Icing conditions as those encountered during various icing processes in nature, can be simulated in this tunnel. The readers are referred to Kermani *et al.* (2007) for more information about the characteristics of this equipment.

Atmospheric ice was accumulated on an aluminum cylinder (diameter 78 mm and length 590 mm) placed in the middle of the test section of the wind tunnel and rotated at a constant speed of 2 rev/min. Before ice accumulation, the cylinder was cleaned with alcohol and set in place for two hours while the system was cooling down. Once accumulation was over, the cylinder was removed from the test section and the accumulated ice was cut with a warm aluminum blade to avoid any mechanical stress that might cause cracks. The resulting ice slices were then carefully prepared using a microtome. The average time interval between ice accumulation and flexural tests was 5 hours. Fig. 1 shows the position of the specimens extracted from the accumulated ice on the cylinder, and the load direction in the mechanical tests.

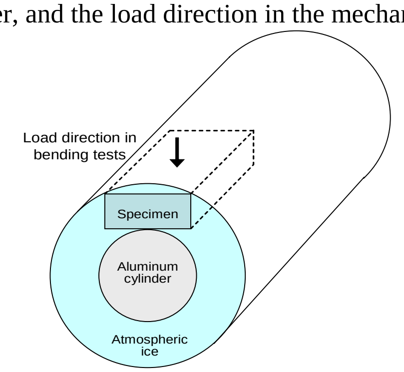

Fig. 1. Schematic illustrating specimen position in accumulated atmospheric ice and load direction during test.

Specimen dimensions, as mentioned in ASTM, were determined by averaging three measurements of the three axes of the samples.

In preparing the specimens, the guidelines recommended by the IAHR working group on test methods (Schwarz *et al.*, 1981) were used.

Air speed that typically leads to natural glaze ice formation ranges from ultra low to medium speeds. In order to make the experimental work more manageable and to obtain a more uniform ice layer, the air velocity value of 10 ms^{-1} was chosen.

The three ambient temperature values -6^{o}C, -10^{o}C and -20^{o}C were selected for the accumulation of atmospheric ice as representative of warm, medium and cold icing conditions.

It was assumed that air pressure was equal to 1 NACA standard atmosphere at sea level (P_{st} =101325 Pa) and that relative humidity ranged from 0.81% to 0.92%.

The LWC for the CIGELE wind tunnel as a function of the difference between the air and water line pressures, air speed and the flow rate of water in the supply line was calibrated by Karev *et al.*(in press). The LWC for icing conditions in nature varies between 0.5 g/m^3 to 10 g/m^3, which is within the range of the wind tunnel. During the calibration, the LWC at the test section of the wind tunnel was measured using the accepted standard technique known as the rotating icing cylinder method (Stallabrass, 1978). An attempt was made in the first stage to obtain atmospheric ice using a LWC of about 1 g/m^3, but the resulting ice was not solid and was characterized by the occurrence of many holes and cavities. Preparing the samples and measuring the mechanical properties of ice in this condition would have been a challenge and was not done. Therefore, LWC was increased to at least 2.5 g/m^3 in order to obtain solid and uniform atmospheric ice without large cavities.

3. TEST CONDITIONS

The mechanical properties of ice can be influenced by test conditions such as temperature, specimen size, loading rate, failure mode, etc. Considering this, the test conditions have been chosen very carefully for this study.

The specimens were accumulated at different temperatures and tested at their accumulation temperatures. However, atmospheric ice accumulated at the typical wintertime temperature (-10^{o}C) was tested at three temperatures -3 ^{o}C, -10 ^{o}C and -20 ^{o}C. The specimens were kept at the test temperature for two hours before each test.

Strain rate is defined in terms of the strain exerted at the bottom of the ice beam. According to the beam–bending theory for three-point loading, the strain rate is given by

$$\dot{\varepsilon} = 6h\delta / L^2$$

where h is the beam height, δ is the cross head speed and L is the beam length.

A wide range of strain rates, 3x10^{-5} s^{-1} to 2 x10^{-3} s^{-1}, was selected, and for each set of parameters at least five specimens were tested. In these tests, the flexural strength of atmospheric ice was determined using a three-point beam bending setup in the push-down mode.

Bending force was applied to the middle of the beam, normal to the axis, at various cross head speeds. According to Schwarz *et al.* (1981), for beams of freshwater ice (which has the closest structure to atmospheric ice) the ratio of beam width to ice crystal size must be ≥ 10 in order to eliminate the grain size effect. Accordingly, the following dimensions were chosen for our specimens: beam width (w) 40 mm, beam thickness (h) 20 mm and beam length (L) 70 mm.

4. RESULTS OF BENDING TESTS

The individual and averaged values of flexural strength of atmospheric ice accumulated at -6 ^{o}C, -10 ^{o}C and -20^{o}C and tested at various temperatures are shown in Tables 1. Flexural strength σ_f was calculated from the simple elastic beam theory using the equation:

$$\sigma_f = \frac{3FL}{2wh^2}$$

where F is the failure load; L is the length of the beam; w and h are width and height of the beam, respectively, measured at the failure plane.

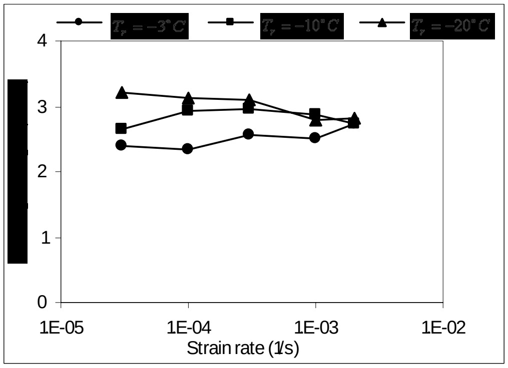

Fig. 2. Flexural strength of atmospheric ice accumulated at -10 °C and tested at various temperatures.

Fig. 2 shows the comparative results of flexural strength at different temperatures. A clear dependency of flexural strength on test temperature for the three lower strain rates is distinguishable in this figure. This trend of increasing strength with decreasing temperature has also been reported by Gagnon and Gammon (1995) for iceberg ice and by Gow and Ueda (1988) for freshwater ice.

Table 1. Results of flexuralstrength tests on ice accumulated at -6 °C, -10 °C and -20°C and tested at various temperatures. (Ta= Accumulation temperature, Tt= Test temperature)

		Ta= -10 °C Tt= -3 °C			Ta= -10 °C Tt= -10 °C			Ta= -10 °C Tt= -20 °C			Ta= -6 °C Tt= -6 °C			Ta= -20 °C Tt= -20 °C		
Row	Strain rate (1/s)	Flexural strength (Mpa)	Ave. Of Flexural strength for Similar Conditions (MPa)	Stand. Dev. (MPa)	Flexural strength (Mpa)	Ave. Of Flexural strength for Similar Conditions (MPa)	ST. Dev. (MPa)	Flexural strength (Mpa)	Ave. Of Flexural strength for Similar Conditions (MPa)	ST. Dev. (MPa)	Flexural strength (Mpa)	Ave. Of Flexural strength for Similar Conditions (MPa)	ST. Dev. (MPa)	Flexural strength (Mpa)	Ave. Of Flexural strength for Similar Conditions (MPa)	ST. Dev. (MPa)
1	3.E-05	2.79	2.40	0.34	2.50	2.65	0.45	3.19	3.20	0.68	2.37	2.61	0.39	2.22	2.63	0.59
2	3.E-05	2.22			2.92			3.67			2.62			3.31		
3	3.E-05	2.33			2.94			4.13			3.24			3.24		
4	3.E-05	1.95			1.94			3.13			2.24			2.20		
5	3.E-05	2.69			2.45			2.11			2.58			2.18		
6	3.E-05	----			3.18			2.97			----			----		
7	1.E-04	2.24	2.33	0.16	2.46	2.92	0.26	2.39	3.12	0.55	2.83	2.45	0.56	2.46	2.53	0.40
8	1.E-04	2.23			3.02			3.52			3.23			2.08		
9	1.E-04	2.51			2.97			3.69			2.15			2.67		
10	1.E-04	2.16			3.11			2.73			1.88			3.13		
11	1.E-04	2.49			3.04			3.28			2.15			2.30		
12	3.E-04	2.95	2.57	0.83	2.88	2.97	0.24	3.97	3.08	0.44	2.30	2.62	0.60	2.74	1.98	0.52
13	3.E-04	3.55			3.26			2.87			2.87			2.12		
14	3.E-04	2.92			3.18			2.96			3.56			1.70		
15	3.E-04	1.75			2.85			2.85			2.06			1.98		
16	3.E-04	1.66			2.68			2.95			2.32			2.17		
17	3.E-04	----			----			2.90			----			1.17		
18	1.E-03	3.44	2.50	0.78	2.86	2.88	0.52	2.51	2.78	0.23	----	----	----	----		
19	1.E-03	2.53			3.28			2.99			----			----		
20	1.E-03	2.92			2.00			2.67			----			----		
21	1.E-03	1.36			3.19			2.68			----			----		
22	1.E-03	2.25			3.10			3.04			----			----		
23	2.E-03	2.63	2.73	0.31	3.41	2.74	0.59	2.63	2.82	0.46	2.07	2.54	0.35	2.60	1.97	0.43
24	2.E-03	2.52			3.02			2.53			2.65			2.11		
25	2.E-03	2.67			2.13			2.76			3.04			1.45		
26	2.E-03	2.77			3.02			3.62			2.51			1.90		
27	2.E-03	3.32			2.10			2.55			2.43			1.79		
28	2.E-03	2.45			----			----			----			1.52		

According to the guidelines recommended by the IAHR working group on test methods (Schwarz *et al.*, 1981), loading times to failure in the order of 1 second yield satisfactory results. In the present study, this corresponds to a strain rate of 2 x10^{-3} s^{-1}. In order to study the effects of strain rate on the flexural strength of atmospheric ice, the specimens have been tested with different strain rates.

The average flexural strength of atmospheric ice at the test temperature of -10 °C at a strain rate of 10^{-4} s^{-1} was calculated to be 2.92 ± 0.26 MPa. So far, to the best our knowledge, there is no published investigation of the flexural strength of atmospheric ice with which to compare our results. In comparison with freshwater ice, however, Timco and Frederking (1982) reported the bending strength of freshwater ice to be 2.20 ± 0.32 MPa and 1.77 ± 0.19 MPa for three-point beam bending , at approximately the same strain rate, with top and bottom in tension, respectively. Dempsey *et al.* (1989), in their tests with four–point–bend beams obtained the bending strength of freshwater ice ranging between 1.5 MPa and 1.7 MPa and between 1.2 MPa and 1.7 MPa for smaller and larger beams, respectively.

The average flexural strength of atmospheric ice at the test temperature of -10°C at a strain rate of 2 x10^{-3} s^{-1} has been found to be 2.74 ± 0.59 MPa in our study. Gow and Ueda (1988) reported values of 2.41 ± 0.29 MPa and 1.59 ± 0.17 MPa at -19°C for the three–point beam with top and bottom in tension, respectively.

The average flexural strength of atmospheric ice at -3°C at a strain rate of 2 x10^{-3} s^{-1} was found to be 2.73 ± 0.31 MPa. Lavrov (1971) reported an average flexural strength for freshwater ice of approximately 2.01 MPa for S1 ice and 2.16 MPa for S2 ice tested isothermally at -3°C to -4°C. Gow and Ueda (1988) reported values of 2.10 ± 0.39 MPa and 1.39 ± 0.27 MPa for S1 ice tested at -5°C with top and bottom in tension, respectively.

At a test temperature of -20°C, for ice accumulated at -10°C the average flexural strength at the strain rate of 2 x10^{-3} s^{-1} was found to be 2.82 ± 0.46 MPa. Gow and Ueda (1988) reported a similar value of 2.57± 0.29 MPa and 1.64±0.12 MPa at -19°C for the three-point-beams with top and bottom in tension, respectively. Fig. 3 shows the comparison between the present values of flexural strength of atmospheric ice (at strain rate of $2x10^{-3}$ s^{-1}) and those of other investigators for freshwater ice and glacier ice. Higher values of flexural strength of atmospheric ice can be attributed to its lower average grain size in comparison with the other types of ice.

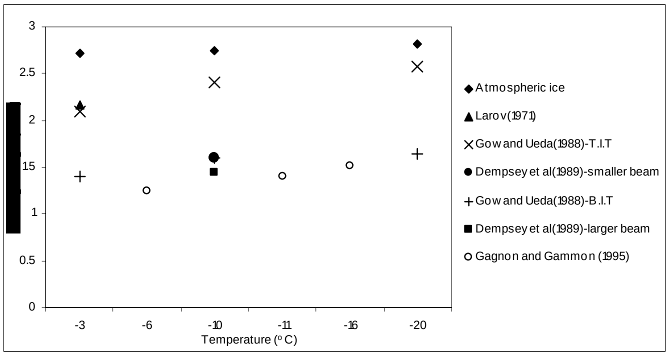

Fig. 3. Comparison of flexural strength of atmospheric ice with values of other researchers for freshwater ice and glacier ice. (T.I.T= Top In Tension; B.I.T= Bottom In Tension)

Timco and O'Brien (1994) reviewed the results of many researchers on the flexural strength of freshwater ice and sea ice for both cantilever and simply supported beam tests. According to their research, the flexural strength of freshwater ice lies within a range of 1 MPa to 3 MPa.

Fig. 4 demonstrates the comparative values of flexural strength of all the three types of atmospheric ice. In Fig. 4, it is observed that the flexural strength of atmospheric ice accumulated at -20 °C and tested at the same temperature is lower than that of the two other types. The reason for these differences will be discussed in the following section.

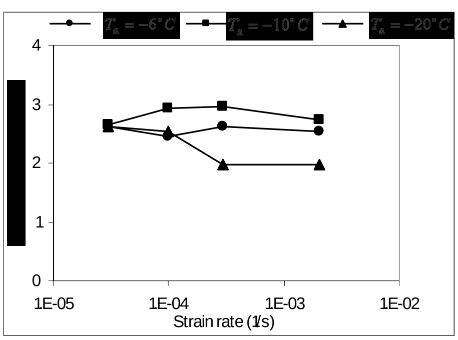

Fig. 4. Flexural strength of atmospheric ice accumulated and tested at various temperatures.

5. GRAIN STRUCTURE AND AIR BUBBLE INCLUSIONS

Thin sections of atmospheric ice accumulated at -6 °C (parallel to the cylinder's axis) reveal that the average grain size of this type of ice is approximately 1.5 mm, and varies from 0.5 mm to 3 mm (Fig. 5).

The air bubble content of atmospheric ice depends on the growth conditions, including air temperature, droplet size, LWC and ice deposit temperature. It was observed that the average diameter of the bubbles in ice accumulated at -6 °C is roughly 0.07 mm, with considerable variation in size (Fig. 6). The porosity of ice (the ratio of the void or bubble volume to the total volume of the ice sample) was approximately 2.9% at the accumulation temperature of -6 °C, based on the measured volume and mass of samples.

Fig. 5. Thin section of ice accumulated at -6 °C. The section is in the same orientation as the top surface of the specimen shown in Fig. 1, where the loading direction is vertical in the image.[8]

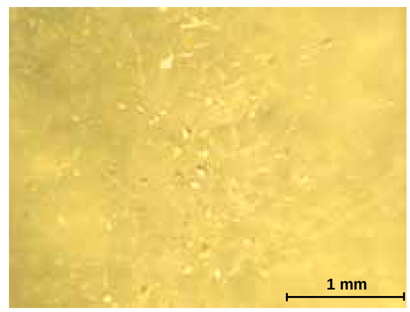

Fig. 6. Thick section showing air bubbles in ice accumulated at -6 °C. The orientation is the same as in Fig. 5 [8].

The grain size of atmospheric ice accumulated at -10 °C is observed to be considerably smaller than that accumulated at -6 °C (approximately 0.5 mm, Fig. 7). The porosity of this type of atmospheric ice was found to be approximately the same as that of ice accumulated at -6 °C, based on measurements, but was likely slightly higher as was evident in the more cloudy appearance of bulk samples in comparison to the ice accumulated at -6 °C. The density of air bubbles for this type of ice is greater than that accumulated at -6 °C (Fig. 8). The average diameter of bubbles for this type of ice is roughly 0.1 mm, with considerable variation in size.

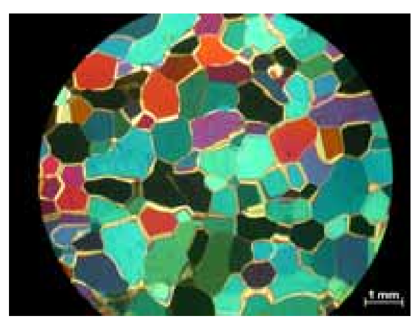

Fig. 7. Thin section of atmospheric ice accumulated at -10 °C. The orientation is the same as in Fig. 5 [8].

A significant number of cavities and possibly cracks are visible in the ice accumulated at -20°C. The presence of these cavities is attributed to the high freezing rate of the droplets, which prevents them from filling the cavities.

The average grain size in this type of ice is less than 0.4 mm, the grain boundaries are more angular than for the ice accumulated at -10 ^{o}C, and the cavities are distinctive (Fig. 10). The porosity of this type of atmospheric ice has been found to be 8.5% owing to the significant amount of cavities and voids.

A thin section perpendicular to the cylinder axis of the ice accumulated at -10 ^{o}C (Fig. 11) shows that at thicknesses greater than about 2 mm, the grains are elongated perpendicular to the cylinder axis.

6. DISCUSSION

In Fig. 2, at the lower strain rates, the strength of the ice appears to increase with decreasing temperature, as expected. At higher strain rates, however, little or no temperature effect is seen.

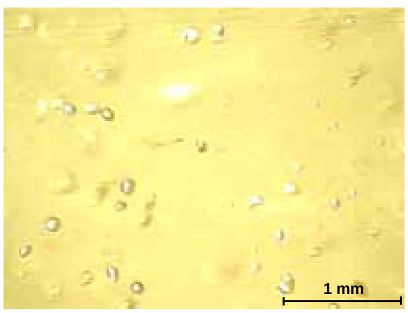

Fig. 8. Thick section showing air bubbles in ice accumulated at -10 ^{o}C. The orientation is the same as in Fig. 5 [8].

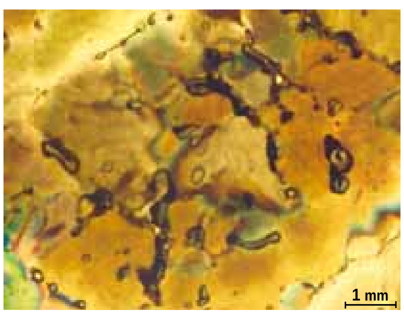

Fig. 9. Thin section showing cavities and possibly small cracks in ice accumulated at -20 ^{o}C. The orientation is the same as in Fig. 5 [8].

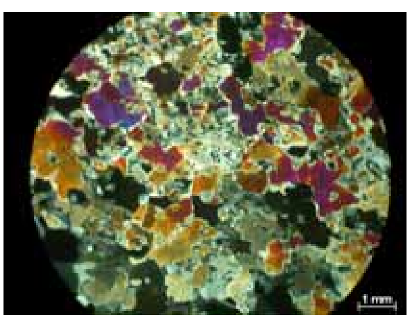

Fig. 10. Thin section showing grain structure in ice accumulated at -20 ^{o}C. The orientation is the same as in Fig. 5 [8].

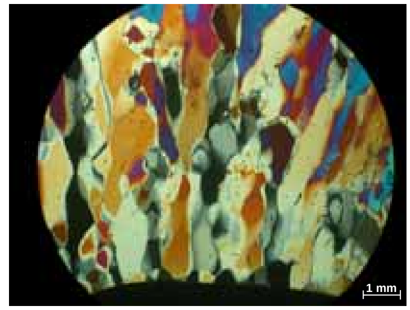

Fig. 11. Thin section showing grains near the cylinder surface (bottom) in atmospheric ice accumulated at -10 ^{o}C. The orientation of the thin section corresponds to the orientation of the end face of the specimen shown in Fig. 1 [8].

Gagnon and Gammon (1995) noticed an increasing trend in flexural strength with decreasing temperature at a strain rate of 10^{-3} s^{-1} in the case of iceberg ice. Gow and Ueda (1988) also observed that increasing trend at a similar strain rate.

From the trends observed in Fig. 2, one can conclude that strain rate and temperature affect the flexural strength of ice, in a small but measurable way. Depending on the temperature, increasing strain rate can either increase or decrease the flexural strength. Gagnon and Gammon (1995) also observed that strain rate has an effect on flexural strength, for iceberg ice specimens whose strength increases with strain rate at –11 °C. While Timco and Frederking (1982) stated that no distinct loading rate effect could be found in their study of the flexural strength of freshwater ice, their data nevertheless show a statistically significant increase in strength with loading rate for simply supported beams with bottom failure, even over the limited range of the loading rates used for the tests. Also, in their cantilever beam tests, a statistically significant decrease in strength with loading rate over a wider range of loading rates is observed. So the relationship of the flexural strength of ice with respect to temperature and strain rates is not fully understood and warrants further study.

As shown in Fig. 4, the flexural strength of the ice accumulated at -10 ^{o}C is higher than that of the two other ice types. The smaller grain size of this ice, as compared to that of ice accumulated at -6 ^{o}C, as well as the colder test temperature (-10 ^{o}C) explain its higher flexural strength. The similar values obtained for flexural strength of ice accumulated at -10°C and tested at -3 °C and that of ice accumulated at -6°C and tested at -6°C (Table 1), despite the warmer test temperature of the former, further demonstrates that the flexural strength of atmospheric ice accumulated at -10°C is higher than that accumulated at -6°C.

The lack of cavities in ice accumulated at -10 ^{o}C compared to the many cavities in ice accumulated at -20 ^{o}C, despite the warmer test temperature, results in a stronger structure and higher flexural strength for the former. In other words, the lower strength observed for the ice accumulated at -20^{o}C can be attributed to the presence of a significant number of cavities which are susceptible to stress concentration. After comparing the average values of flexural strength of the ice accumulated at -10 ^{o}C and tested at -20 ^{o}C and the corresponding values for the ice accumulated and tested at -

20 ^{o}C, we may conclude that the flexural strength of ice accumulated at -10 ^{o}C is greater than that obtained at -20 ^{o}C.

The difference between the flexural strengths of the three types of atmospheric ice is more noticeable at higher strain rates where the cracks propagate more rapidly into the specimen. In Fig. 4, the flexural strength of the ice accumulated at -20 ^{o}C and tested at the lowest strain rate (3 x10^{-5} s^{-1}) is almost the same as that of the ice accumulated at the other temperatures.

The dissimilarity between atmospheric and freshwater ice is at the source of some differences between the results of the present study and those of other investigators for the flexural strength of freshwater ice. Differences in grain size, void ratio, shape and size of bubbles and grain growth direction are some examples of this dissimilarity.

As mentioned earlier, the average grain size for atmospheric ice accumulated at -10 ^{o}C and -6 ^{o}C is 0.5 mm and 1.5 mm, respectively. In the tests of Gow and Ueda (1988) and those of Timco and Frederking (1982), however, the average grain size was found to be between 4 mm to 8 mm and 1 mm to 6 mm, respectively.

Another important issue that can cause some differences between the results of our tests and those of other researchers is the test sample size, which is known to affect mechanical properties (Dempsey *et al.*, 1989). The specimen dimensions in our study were 40 mm wide, 20 mm thick and 70 mm long. Timco and Frederking (1982) used sample sizes of 60 mm x 100 mm x 400 mm in their study. The height and width of the samples used by Gow and Ueda (1988) were in a range of 78 mm to 140 mm and the average beam length was between 710 mm and 1020 mm. The large difference in sample size between the present study and the previous ones is likely responsible for some of the differences in the results. The inherent scatter of the test results may also have contributed to the discrepancies.

7. CONCLUSIONS

The flexural strength of different types of atmospheric ice was measured using the three-point loading of beam approach. The ice was accumulated on a rotating cylinder in the CIGELE atmospheric icing wind tunnel at LWC of 2.5 g/m^{3}, wind speed of 10 m/s and various accumulation temperatures. The ice accumulated at -10 ^{o}C was tested at -3 ^{o}C, -10 ^{o}C and -20 ^{o}C. The accumulated ice at -6 ^{o}C and -20 ^{o}C was tested at the same temperature as accumulated. More than 120 tests were carried out to measure the flexural strength of atmospheric ice. The results of these tests show that at the lower strain rates the strength of the ice increases with decreasing temperature, but no temperature effect is observed at the higher strain rates. It is also observed that, depending on temperature, increasing the strain rate can increase or decrease the ice strength. In view of these observations, the flexural strength behavior of ice with respect to temperature and strain rate needs further investigation. The flexural strength of atmospheric ice accumulated at -10 ^{o}C has been found to be higher than that of the two other types of atmospheric ice due to its stronger structure owing to its smaller grain size and its relative lack of cavities. Also, it has been found that the flexural strength of atmospheric ice accumulated at - 20 ^{o}C decreases with increasing strain rates. The differences between the structure of atmospheric ice and freshwater ice, as well as those between the specimen dimensions in the current study and those of previous studies, lead to discrepancies between our results and those of other investigations on freshwater ice.

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