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A contribution to the study of the compressive behavior of atmospheric ice

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ABSTRACT

In the last decades, research on atmospheric icing of structures such as power transmission lines has attracted much interest. Accumulation and the shedding of atmospheric ice from overhead transmission lines and ground wires may cause their rupture and tower collapses, leading to power outages.

The present work concerns a study of the compressive strength of atmospheric ice, under different experimental conditions such as strain rate, temperature, and porosity. For this reason, ice was accumulated in the closed loop wind tunnel at CIGELE (Industrial Chair on Atmospheric Icing of Power Network Equipment), under three temperatures (−20, −15 and −5 °C). The wind speed inside the tunnel was set at 20 m/s in order to obtain a mean volume droplet diameter (MVD) of 40 μm and a liquid water content (LWC) of 2.5 g/m^3. Each type of ice was tested at the same temperature at which it had been accumulated. A tomographic analysis was carried out on a small specimen (cylinder of 1 cm diameter × 2 cm length) for each temperature in order to quantify the porosity and determine the grain size and their distribution.

The obtained results show a strong dependence of the compressive strength on temperature, strain rate and porosity. The ductile–brittle transition was identified within a strain rate ranging between 10^{-4} s^{-1} and 10^{-3} s^{-1}. It was found that compressive strength increases with decreasing temperature for deaerated ice. However, for atmospheric porous ice, compressive strength increases until −15 °C, then decreases for lower temperatures. Compressive strength of atmospheric ice is highly dependent on porosity, which is related to the amount, size and distribution of pores inside the ice.

1. Introduction

In northern environments, structures such as power electrical transmission lines, aircrafts, wind turbines, and railways are subjected to winter storms and icing. The atmospheric icing phenomena, which are the result of water compaction (vapor or liquid at negative temperatures) into ice, can affect the stability of transmission lines (wind/vibration), the network efficiency and the safety of the population (breakdowns) (Farzaneh, 2008). To avoid or reduce the adverse consequences of icing, it is essential to understand the phenomenon of ice adhesion and accumulation on power lines and then to identify the mechanical behavior of ice in such conditions.

Atmospheric icing is a meteorological phenomenon that is manifested by the deposition of supercooled water drops or droplets on a cold surface (at a temperature below 0 °C) (Lozowski and Gayet, 1988). Depending on atmospheric conditions, including air temperature, rate of precipitations, liquid water content, pressure, humidity or wind speed, various types of atmospheric ice can be observed in nature: soft rime, hard rime, glaze or wet snow.

While the mechanical properties of fresh water and saline ice have been widely discussed in the literature as functions of different environmental and structural parameters such as temperature, strain rate, grain size and orientation, and ice type (Michel, 1978; Sinha, 1981; Currier and Schulson, 1982). The mechanical behavior of atmospheric ice has been rarely studied systematically (Druez et al., 1986; Kermani et al., 2007).

The mechanical properties of atmospheric ice vary considerably with environmental and microstructural conditions (Mohamed and Farzaneh, 2011), small fluctuations in temperature, liquid water content, mean volume droplet diameter or the strain rate during loading, which induces a significant variation in the mechanical response of the ice respectively to different types of loading. Depending on strain rate, ice behaves differently. For low strain rates, ice has a ductile response, while it displays linear elasticity until brittle fracture for high strain rates (Sinha, 1982).

The observations made by Kermani (Kermani et al., 2007) on the compressive behavior of atmospheric ice under different temperatures

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Fig. 1. Accumulated atmospheric ice on the rotating cylinder.

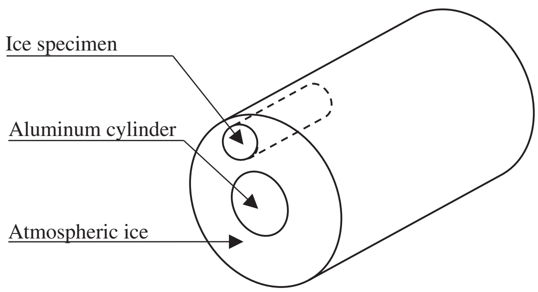

Fig. 2. Schematic illustration of accumulated atmospheric ice and the specimen cut.

and strain rates showed consistency with earlier investigations on fresh water ice (Hawkes and Mellor, 1972; Schulson, 1990). Through these investigations, brittle failure was shown to occur at low temperature and high strain rate. However, the presented results are too scattered to allow for the establishment of a distinctive relationship between the brittle failure of ice and different structural and environmental parameters. Therefore, more experimental studies are necessary to understand the brittle failure of ice under compressive strength.

On the other hand, fractures in polycrystalline materials are commonly observed at homologous temperature greater than 0.3 to 0.4 T_m, where T_m is the melting point in Kelvin scale (Sinha, 1984). This mode is characterized by low ductility as observed from the stress–strain curve. At elevated temperature, intergranular fracture is dominated by three stages: initiation, growth, and coalescence of intergranular cavities and cracks. At a microscopic scale, nucleation of microcracks and cavities was observed at the triple points, grains boundaries, irregularities, while at a bigger scale, the existence of pores is considered as the preferred sites of crack initiation and propagation.

Compared to other types of ice, atmospheric ice presents a high porosity, which is related to the accretion mechanisms involving the copresence of water droplets and air bubbles during the freezing process. Earlier investigations on the mechanical behavior of atmospheric ice omitted the porosity effect, and considered just structural and environmental conditions (Mohamed and Farzaneh, 2011; Kermani et al., 2007; Eskandarian, 2005).

In the present study, the compressive strength of atmospheric ice has been studied as a function of temperature, strain rate and porosity. For this purpose, ice was accumulated in the CIGELE icing wind tunnel. In order to evaluate the porosity effect on the compressive strength of atmospheric ice, experimental tests were carried out on ice samples obtained by freezing deaerated fresh water.

The first section of the paper introduces the experimental procedure followed to prepare atmospheric ice samples. Details are given on atmospheric ice preparation conditions, specimen cutting and test procedures. The second section presents microstructure observations, the X-Ray microtomography analysis to study the ice microstructure, and the procedure to determine grain size and porosity. The last section of the paper discusses the obtained results.

2. Experimental procedures

Mechanical properties of ice are subject to changes under several parameters such as temperature, strain rate, anisotropy and porosity. Therefore, one of the main objectives of the present study is to elucidate the effect of those parameters by carrying out compressive tests on cylindrical ice specimens prepared under different laboratory conditions.

2.1. Atmospheric ice preparation

Atmospheric ice was prepared under specific conditions created in the CIGELE wind tunnel, more details on the wind tunnel can be found in Refs. Eskandarian (2005) and Kermani (2007).

This technique was used in order to simulate the natural atmospheric icing process. Water was injected into a cold airstream through nozzles located at the trailing edge of a spray bar. Three independent supply lines provided air and water to the nozzles. The flux, the velocity, and the air speed were controlled using a computer program, theses parameters were set to generate droplets with a mean volume droplet diameter (MVD) of 40 μm and a liquid water content (LWC) of 2.5 g/m^3. A computer program allowed to control the flux and velocity inside the tunnel, and air speed was controlled to generate droplets with a mean volume droplet diameter (MVD) of 40 μm and a liquid water content (LWC) of 2.5 g/m^3. Atmospheric ice was accumulated on a rotating aluminum cylinder (78-mm diameter and 590-mm length). The cylinder was carefully cleaned with hot water and soap before each set of experiment. Then it was placed in the middle of the test section of the wind tunnel, and fixed by each edge against a rotor making 1 rpm, making the thickness distribution of ice uniform, as illustrated in the Fig. 1. The distance between the cylinder and spray nozzles was large enough for the droplets to reach kinetic and thermodynamic equilibria.

Depending on accumulation conditions such as air temperature, velocity and liquid water content, the time needed to grow a sufficient thickness of ice on the cylinder varied from 2 to 4 h, sometimes up to

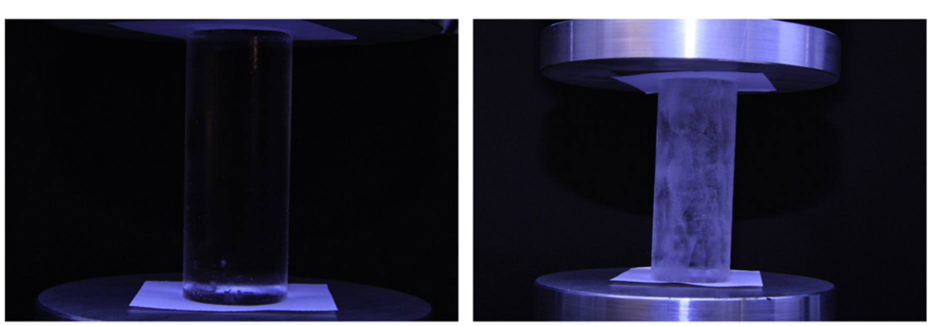

Fig. 3. Cylindrical ice specimens mounted between the compression machine plates at −5 °C: on the left, transparent deaerated ice, on the right porous atmospheric ice.