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DETERMINATION OF ICE ADHESION AND ICE PROPERTIES IN ORDER TO DETERMINE ICE SHEDDING PROCEDURE OF COATING SYSTEMS

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Abstract: In this work, we set forth a method to measure ice strength and ice adhesion in tension in order to support an engineering assessment of how coating systems used on wind turbine blades may be assessed so that their potential can be fully realized. A crucial aspect of this approach is that the mechanical testing is performed in an icing tunnel.

INTRODUCTION

The objectives of these tests are experimental study work of fracture of impact ice and ice accretion rate on coated specimens. The experimental procedure was carried out at Cranfield University Icing Tunnel Facility.

Two sets of tests have been performed.. In the first set of tests was measured how the wind speed affects to the ice adhesion, so that, the controlled variable was the wind speed, at 30, 40, 50 and 60 m/s. A reference material currently employed by the company was employed. In the second set, it was measured the adhesion strength of ice to different materials that the company had in mind to substitute the reference material. The constant parameters maintained for the entire test work are LWC = 0.3 g/m^3, temperature = -5 ^{o}C and MVD = 0.20. These were selected to represent conditions of interest to wind turbine manufacturers and fall comfortably within the capability of the icing tunnel.

The technique to calculate fracture energy employed in this first part for tensile adhesion is based on the method by Andrews et al (1984) for tensile stresses for static ice and on impact ice by Hammond (1996).

Whilst the work described here deals with the tensile fracture and adhesive forces involved with ice shedding, further work is also underway using a shear testing apparatus. This new equipment allows us to produce interfacial shear fracture under the same conditions.

1. RESULTS AND DISCUSSION

The results from the first set of tests show the influence of the impacting wind speed on a reference material. It is observed that the impacting wind speed has no effect on ice adhesion for the materials tested in the testing range (fig 1) The second set of tests was performed to compare materials provided by the sponsor with the reference one and each other, in research to find low adhesion materials to be employed in wind turbine blades. Fig 2 shows the fracture energies for the seven alternative materials tested.

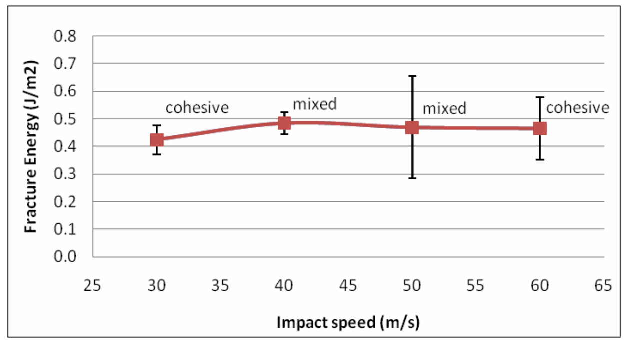

Figure 1: Ice adhesion at different wind speeds

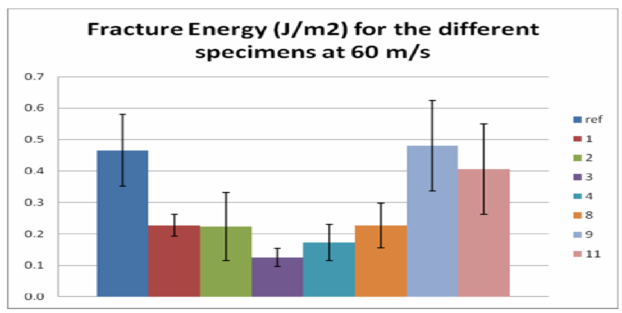

Figure 2: Ice adhesion at 60m/s to different materials

2. CONCLUSION

We have been able to grow impact ice and measure works of tensile adhesion and icing growth rate in an ice tunnel. The ice tunnel facilities are found to be a tool to compare materials under icing conditions. Different wind speeds significantly affect the rate of ice accretion.

Fracture Energy in tensile direction is not affected by impact speed in the speed range tested and for the working conditions.

Significant differences in ice adhesion were found between materials tested.

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Abstract - **With the expansion of the use of wind turbines, both in terms of the numbers of units and the geographical and marine range of environments under which they operate, a significant area of interest is on how well wind farms can be made to operate in atmospheric icing and with what level of associated hazard to the equipment itself and to surrounding structures and people. In this work, we set forth a method to measure ice strength and ice adhesion in tension in order to support an engineering assessment of how coating systems used on wind turbine blades may be assessed so that their potential can be fully realized.**

A crucial aspect of this approach is that the mechanical testing is performed in an icing tunnel while the tunnel is running. Without this, the ice may become unrepresentative of the natural condition due to annealing effects and changes in thermal stresses.

The mechanical data shows that there can be significant differences between the adhesion of ice to different substrates in the range of conditions tested.

The long term objective is that with sufficiently realistic ice fracture and ice adhesion data, it will be possible to determine some aspects of the shedding of ice from rotating turbine blades including shed fragment mass.

Keywords: **Icing; wind turbines; ice adhesion; coatings**

I. WIND ENERGY IN COLD CLIMATES

For many cold regions around the world wind energy proved to become an important contributor to power generation. In 2007 wind generated electricity contributed 1% of the total global demand [1]. The target of the European Union by the year 2020 is to produce 34% of electricity by renewable energy in which 14% of this will be contributed by wind energy [2].

There is a substantial potential; for wind energy in areas with cold climates, where wind turbines are exposed, at times, to low temperatures and moisture. Icing events can be frequent and potentially long lasting if nothing is done to mitigate the influence of atmospheric icing [3].

In the first instance, as the ice builds, it affects the aerodynamics (efficiency) [4] and degrades wind turbine performance [5]. Complete loss of production can be caused in severe icing conditions where torque drops to zero and turbine stops [5].Whilst the wind turbine is operating during icing event it is assumed that the leading edge of the rotor blade collects ice and shed it off frequently, due to centrifugal and aerodynamic forces [6]. Ice throw from the turbine blades can be harmful to those in the vicinity of operating iced blades [6,7]. During the ice accretion and detaching process wind turbines may face heavy vibrations and can cause the collapse of the wind turbine if not stopped [6].

The properties of the ice and rate at which it forms can vary widely depending on the prevailing conditions. The factors which most strongly affect this are: the concentration of droplets in the air (LWC-liquid water content in g/m^3, their size (MVD-median volume diameter in microns), the temperature (total temperature), the wind speed, the duration, the chord length and shape of the blade, and type of structure (e.g. thermal characteristics and stiffness). The resulting ice may be rime, glaze or mixed.

The shape, distribution and properties of ice will vary considerably depending on these icing conditions and the motion of the turbine blade and quite possibly on the location on the blade itself. Glaze ice is transparent, hard and forms when it is the rate of heat transfer which limits the local freezing rate. Rime ice is white and opaque and forms when the water droplets freeze immediately on the impact.

The mitigation strategies described in the literature can be divided into two types: Active and Passive strategies. Active ones involve external energy inputs such as electrical, thermal and mechanical techniques to prevent or remove the ice from the blade surface. In passive systems inherent physical properties of the blades are used to prevent or eliminate ice from the blade surface [3,5].

Although active-deicing systems have gained a lot of attention and have proven efficient in reducing ice adhesion, these systems may not be ideal for general wind farm operations due to the added complexity and the associated manufacturing and maintenance costs.

Passive mitigation systems, especially coating systems could be inexpensive and easy to apply [8]. Special coatings which having Icephobic characteristics can shed ice more easily due to the reduction of shear bond strength between ice and the blade surface. These have been investigated by wind turbine industry [9,11].

Low surface energy materials are gaining attention as potential icephobic materials. These materials have been investigated extensively by different methods [8,9,10,11,12]. The present experimental study expands work in this area in the hope of the understanding of ice adhesion to coating systems by a method developed in-house in Cranfield University.

II. EXPERIMANTAL METHODOLOGY

The experimental procedure was carried out at Cranfield University Icing Tunnel Facility (fig 1) [13], in a 760x760 mm wooden test section. The objectives of these tests are experimental study work of fracture of impact ice and ice accretion rate on coated specimens. The technique employed in this first part for tensile adhesion is based on the method by Andrews et al (1984) for tensile stresses for static ice and on impact ice by Hammond (1996). Andrews et al prepared their ice by freezing distilled water on the end of the substrate while Hammond prepared his ice in icing tunnel by placing cylinders faced to oncoming flow and using spray water nozzles. Whilst the work described here deals with the tensile fracture and adhesive forces involved with ice shedding, further work is also underway using a shear testing apparatus. This new equipment allows us to produce interfacial shear fracture under the same conditions.

The constant parameters maintained for the entire test work are LWC = 0.3 g/m^3, temperature = -5 ^{o}C and MVD = 0.20. These were selected to represent conditions of interest to wind turbine manufacturers and fall comfortably within the capability of the icing tunnel.

The investigation consists of two sets of experiments. The first set of tests is performed to reveal the ice adhesion and ice growth rate on a reference material over a range of wind speed. The wind speeds used were 30, 40, 50 and 60 m/s. This range represents the variation of the relative wind speed from the tip to the near hub in the real case of the wind turbine rotor blade. This reference material is the one employed currently for the company to coat the blades. A second set of tests is performed at constant speed, in order to evaluate the ice adhesion to other materials that the company had in mind to substitute the reference material.

The tensile test rig consists of a series of de-mountable cylinders faced with the test material. There is a hole in the centre of each cylinder through which gas is used to apply pressure to the ice/substrate interface. The hole is caped with a thin PTFE disc to prevent it from becoming blocked and to define the loading geometry. A constant spray period of 30 minutes for each run was set arbitrarily to ensure the ice accumulated on the specimen has a thickness above 15 mm. This thickness allows plain strain conditions, so that, Linear Elastic Fracture Mechanics based equations by Andrews can be employed to calculate the Fracture Energy *FE* [1]. When ice is thick enough, pressure is applied from a pressurized bottle. Such that, pressure rises approximately 10 Bar/s until fracture occurs. The geometry of the load application arrangement is defined by the thin PTFE disc which has the function of acting as a crack starter.

Output data taken from this test are critical pressure to shed the ice away, ice thickness and percentage of adhesive fracture (fig 2a). An oscilloscope is used to record the critical pressure signal. The percentage of adhesive fracture is the percentage of area clean of ice surrounding the crack starter location (fig 2b). Ice thickness is estimate visually (fig 3). These outputs are variables in Andrews' equation to get the Fracture Energy which is the indicator of the ice adhesion strength.

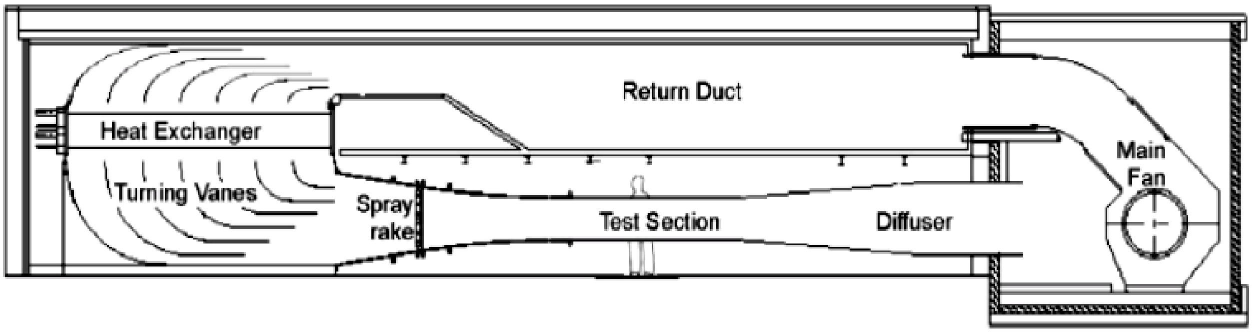


Figure 1. Cranfield University Icing Tunnel Facility, Hammond and Luxford (2003)

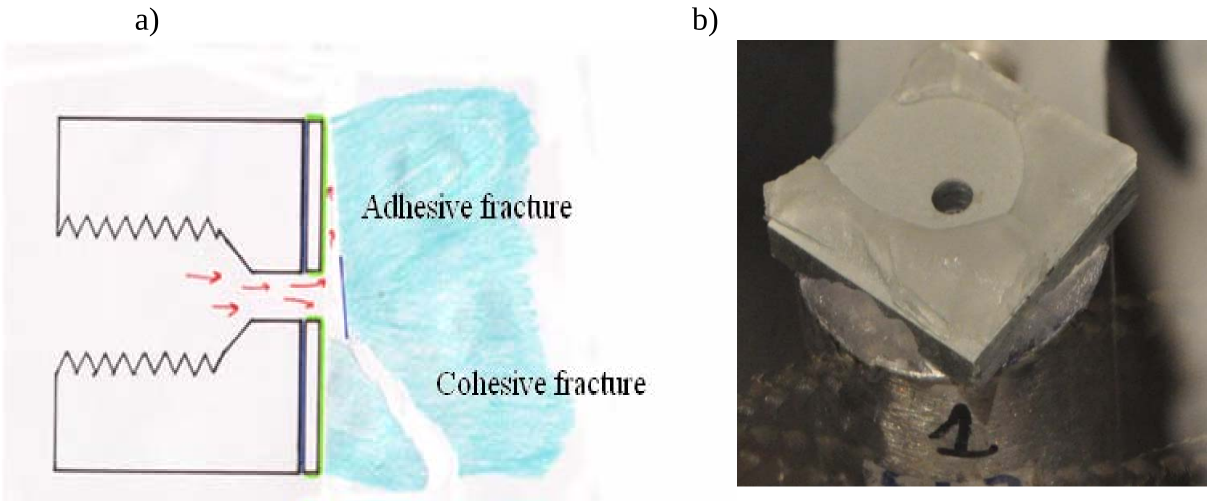


Figure 2. (a) Fracture criteria according to crack propagation (Hammond, 1996) (b) Real case for mixed mode

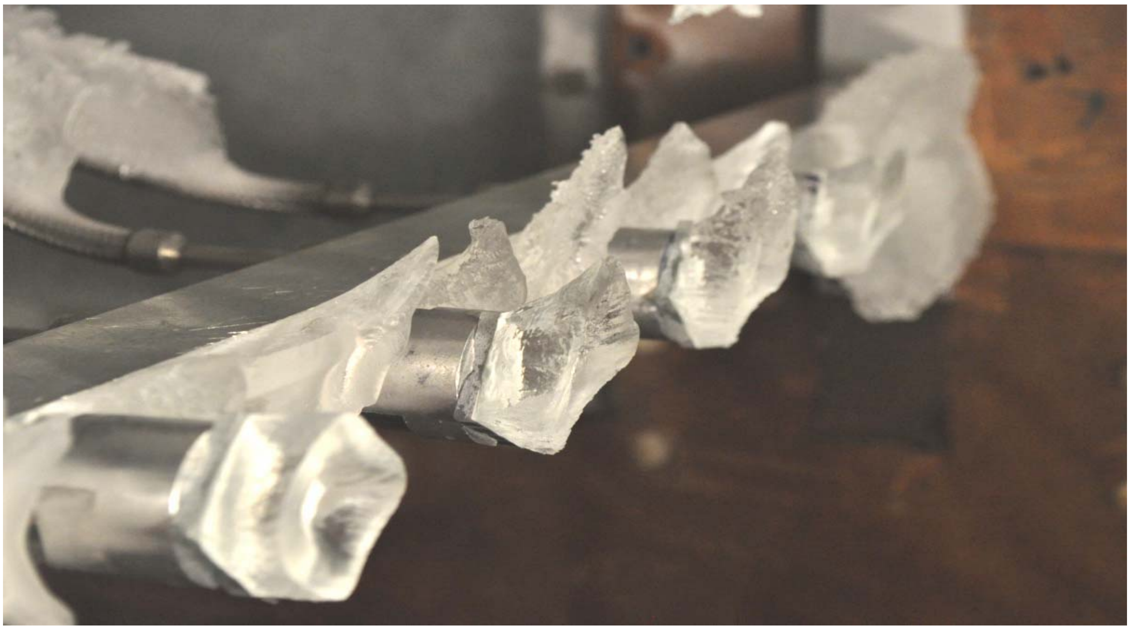


Figure 3: Test rig with secured to icing tunnel and (glaze) ice accreted on coated substrate

III. MATERIALS OVERVIEW

Eight different materials were employed in the benchmarking set of tests, including the reference one. All the materials including the reference one are polymeric nature materials. The formulation is proprietary and, therefore, is not detailed in this paper.

IV. RESULTS

Results from each set of tests can be seen in figures 4, 5 and 6.

The results from the first set of tests show the influence of the impacting wind speed on a reference material for the range of speeds and the described conditions.

It is observed that the impacting wind speed has no effect on ice adhesion for the materials tested in the testing range. The results show that adhesion strength for the reference material has an average value of 0.4 - 0.5 J/m^2 at any of the speeds tested, at the same conditions. The fracture mode for the reference material is found to be cohesive or mixed (adhesive and cohesive, although it is observed that cohesive mode is predominant). Fracture for the tested conditions is found in the transition region between adhesive and cohesive mode, slightly closer to the pure cohesive fracture region. For these conditions, the work of fracture is found to be the same order as the adhesion work in the interface, and crack may propagate either on the interface or through the ice. The fracture energy determined is found to be in the transition region between cohesive and adhesive mode. The probability of getting the crack to spread in the interface, though, is lower according to the recorded results.

The definitive Fracture Energy values are obtained through Weibull statistical analysis. The number of data points obtained for each test is 5 data points for 30 m/s test (4 accepted + 1 censored to Weibull analysis), 6 data points for 40 m/s one (5 accepted + 1 censored for Weibull analysis), 7 data points for each 50 m/s and 60 m/s ones (all accepted). According to the results showed in figure 4, the reference database to perform the second set of tests will be 60 m/s test, whose number of data points is the highest, giving a reliable average Fracture Energy value, and the dispersion is acceptable (around 10%).

The ice accretion rate for this first set of tests is observed in fig 5. It shows that impact wind speed has direct effect on the speed the ice grows. The trend line in the graph represents the average accretion rate recorded in every data point, the bars represent the maximum and minimum values recorded of accretion rate, which represent the richest and driest regions of the cloud respectively.

The second set of tests was performed to compare materials provided by the sponsor with the reference one and each other, in research to find low adhesion materials to be employed in wind turbine blades. It is observed in figure 6 that all materials except #9 had better behavior than the reference one (currently employed). Fracture Energy is found to be reduced around 70 % in specimen #3 compared to the reference one. Another source of interest for some materials is the fact that the fracture is adhesive. Those specimens have the lowest ice adhesion strength except the specimen #11. This one shows adhesive fracture but requires a high amount of energy. The energy required to fracture through the interface is still lower than the one required for the crack to propagate through the ice. The icephobicity of the material and the viscoelastic behavior might lead to this situation.

Lowest-adhesion materials (#3 and #4) have in common a bright varnished-like surface.

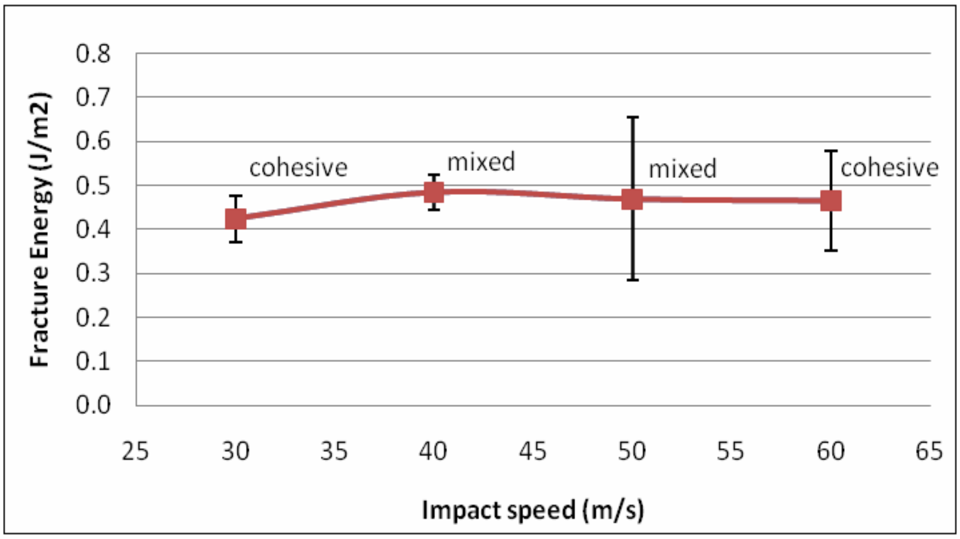


Figure 4: FE at different wind speeds and fracture mode.

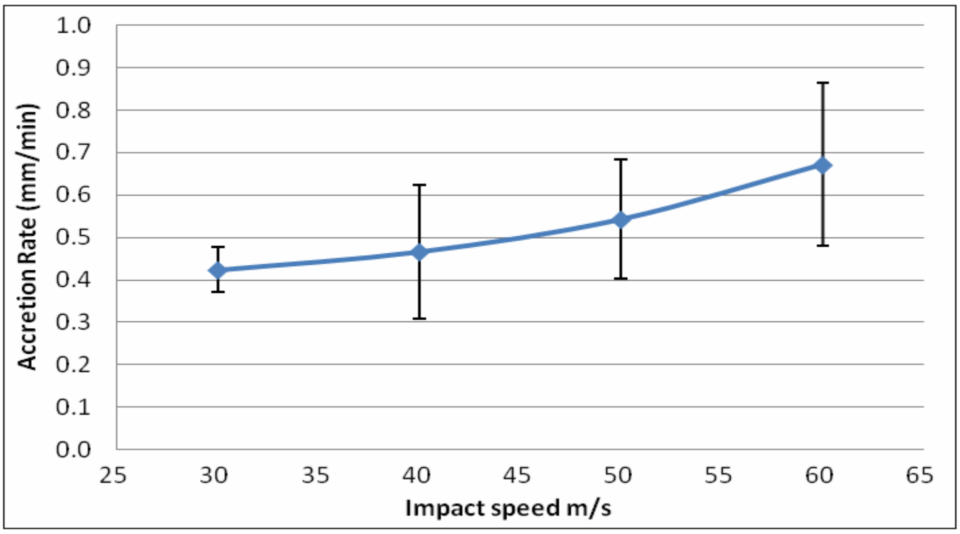
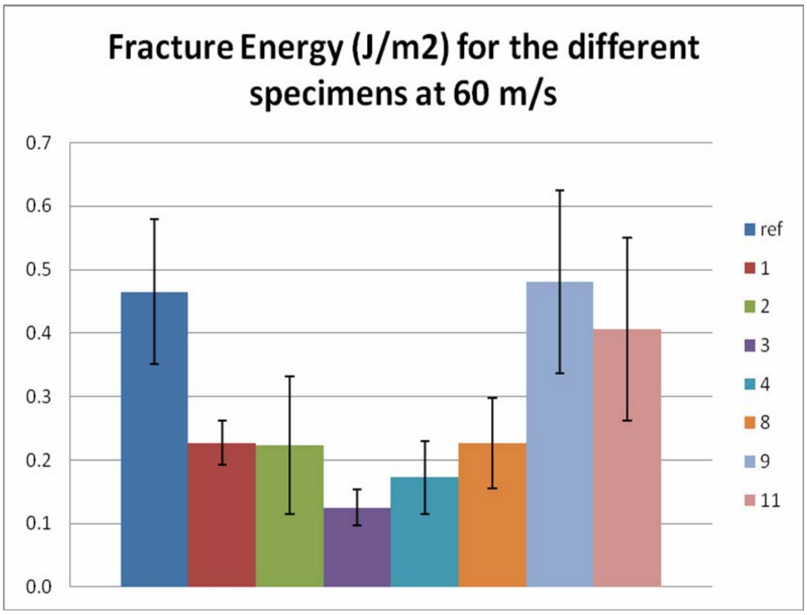


Figure 5: Ice accretions rate at different wind speeds.



Mat code	average FE (J/m2)	fracture mode
ref	0.465	cohesive
1	0.227	adhesive
2	0.223	adhesive
3	0.125	adhesive
4	0.172	adhesive
8	0.226	mixed
9	0.481	cohesive
11	0.406	adhesive

Figure 6: Comparison of FE values and fracture mode for various blade coating materials tested

V. CONCLUSIONS

- We have been able to grow impact ice and measure works of tensile adhesion and icing growth rate in an ice tunnel. The ice tunnel facilities are found to be a tool to compare materials under icing conditions.

- Fracture Energy in tensile direction is not affected by impact speed in the speed range tested and for the working conditions. Ice tensile adhesion is therefore independent of the relative impact and it is the same at the tip and hub of the blades.

- Significant differences in ice adhesion were found between materials tested as shown in figure 6. The most potential materials to provide easy ice shedding, and therefore, be employed as coating for fan blades, are those with low adhesion (low FE), adhesive fracture mode preferred. Using these measurements and techniques we expect to be using materials selection in such a way as to improve the performance of wind turbines in icing areas.

- The specimens with the lowest adhesion strength were found to have a thick, very bright, varnished-like top layer, which might actuate as icephobic. The top layer is found to have the highest effect on the tensile adhesion.

- Among the materials, a pattern was found between Fracture Energy and fracture mode. The lowest energies were found to occur when the fracture was adhesive. However, there is an exception in material #11, which has a relative high fracture energy and adhesive mode. Viscoelasticity (losses and storage capacity) and residual stresses might have high effect on this.

- Different wind speeds significantly affect the rate of ice accretion as illustrated in Figure 5, although the relationship is not proportional as it would be expected, that is, doubling the speed does not double the thickness of the ice accumulated. The reason is in the type of ice: glace ice. This type of ice forms in a slow-freezing process, so not all the impacting water freezes, but forms an exposed liquid layer. Further droplets impacting may splash away or run back, although we could not quantify the percentage of the water lost in each process. It is expected the accretion rate to be linear if the type of ice is rime (fast freezing type).

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