Investigation of Using Icephobic Coatings on a Cable Stayed Bridge

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Abstract: **Icing is a significant challenge that affects structures in many countries. Bridges are an example of structures that may be severely affected by atmospheric icing. The Veterans' Glass City Skyway (VGCS) is a single pylon cable stayed bridge with a main span of 375 m in Toledo, Ohio which was opened to traffic in 2007. The VGCS is owned by the Ohio Department of Transportation (ODOT). Six major icing events have occurred on the bridge which led to the closure of bridge lanes and damaged cars. Therefore, over 80 anti-icing/de-icing technologies were investigated. In addition to considering active and passive technologies, bridge management was considered as an approach to assist the bridge operators.**

Tests on icephobic coatings were conducted at the University of Toledo (UT). An icing tunnel was used to conduct experiments with conditions similar to natural icing scenarios. Three different coatings were tested in the icing tunnel. Based on the results of the icing tunnel test, one coating was selected for testing outdoors in simulated icing events. The stay cable sheaths of the VGCS are made of stainless steel, which offers aesthetic and life cycle cost advantages. Because the stay appearance is important, in addition to preventing ice build-up, being durable enough to last through several winters, and being economical, the coating must not alter the appearance of the stays.

None of the coatings tested performed the anti-icing function effectively. Under the same conditions and over the same duration, the ice layer accumulated on the coated specimen was thicker than that on the uncoated specimen. The results showed that water would bead on the coating, which initially prevented ice from forming directly on the stainless steel surface. However, rather than running off the coating, the water droplets would freeze rapidly on top of the coating. This resulted in a craggy, uneven surface that trapped water effectively, which in-turn led to an increase in ice accumulation rate compared to an uncoated specimen.

Other techniques such as chemicals and internal heating were also tested in this project. Overall, no technique, active or passive, met the operational requirements for the bridge. Therefore, ODOT elected to monitor the conditions on the bridge and protect the traveling public by closing traffic lanes when there is a risk of ice fall. An automated real time monitoring system (dashboard) was built to identify possible icing conditions.

Keywords: icing, bridges, coatings, anti-/de-icing

Introduction

Icing is a worldwide problem that many structures suffer from. In the United States and lower part of Canada, 36 cable stayed bridges are open to traffic, under construction or proposed, and 32 located in or near regions where damaging ice storms have been reported historically. Furthermore, suspension bridges or other bridges with above deck superstructure are prone to the icing problem [1]. As ice accumulates on the stays, it may resist falling for days until the right condition for ice shedding occurs, which will lead to either the closure of lanes or the whole bridge to protect travellers from ice falling. Lane closure not only results in inconvenience to motorists, but economic loss as well. Therefore, several anti-icing/de-icing technologies were investigated in order to solve this problem.

In this study, three icephobic coatings were tested, (1) aliphatic petroleum distillates with proprietary additives, (2) epoxy polymers, silicate mesh with new melt-point-depressants, and (3) fluorocarbon polymer and aliphatic, moisture-cure, three-part polyurethane. Experiments were conducted at the University of Toledo's (UT's) icing wind tunnel and icing experiment station.

I. Veterans' Glass City Skyway Bridge and Weather History

The Veterans' Glass City Skyway (VGCS) is a large single pylon cable stayed bridge in Toledo, Ohio, USA with a main span of 375m and carries three lanes of traffic in each direction with average daily traffic count of 50,000. The stay sheaths are brushed stainless steel, which was chosen because of its lower life cycle cost and aesthetics. It is owned and operated by the Ohio Department of Transportation (ODOT).

Since the opening of VGCS in July 2007, six major icing events have occurred. Examples of precipitation types that may occur during icing events include rain, freezing rain, ice pellets, and snow, or a mix [2][3]. The main cause for five of the six events was freezing rain. Table 1 shows a summary of all icing events.

Because the icing events posed a potential threat to the traveling public and have a significant economic impact, a broad investigation was conducted in order to review all the identified anti/de-icing technologies. Based on this investigation, both active and passive technologies were identified as having some potential according to their efficiency, cost, and environmental friendliness[4][5].

Table 1: VGCS Icing Event History[6]

Ice Event	Ice Accretion	Ice Shedding Trigger	Ice Persistence	No. of Lanes	Damaged Vehicles
December 2007	Freezing rain and fog	Rain with temperature above freezing	2	2	Yes
March 2008	Snow, rain, and fog	Sun with temperature above freezing	1	2	Yes
December 2008	Snow and fog; freezing rain and fog	Rain, gusty winds and temperatures above freezing	7	2	No
January 2009	Freezing rain and fog	Gusty winds, temperature above freezing	10	1	No
February 2011	Freezing rain, clear	Light wind, overcast, and temperature above freezing	4	All	No
January 2015	Freezing rain and snow.	Gusty winds and overcast, remaining ice sublimated/melted of stays following day when ambient air temperature was above freezing	4	All	No

II. UNIVERSITY OF TOLEDO TESTING FACILITIES

A. Icing tunnel

In order to conduct experiments with scenarios similar to a natural environment, an icing tunnel was designed and built by the University of Toledo. The icing tunnel consists of two main parts, i.e. freezing room and a tunnel system. All the icing tunnel parts are shown in Figure 1[7].

Figure 1: UT Icing Tunnel

The icing tunnel is a closed loop system. The cooling unit is capable of keeping the temperature constant as low as -20°C. A multispeed fan was installed for adjusting the wind speed. The test section is made from a clear tube to allow for photography. The test section has a misting system to simulate rain and mounting system to support the specimen.

B. UT Icing Experiment Station (Scott Park)

An icing experiment station was set up at the University of Toledo's Scott Park Campus in order to better understand the nature of icing events, to conduct icing experiments regardless of the natural precipitation, and to minimize the risks to the investigators. Three full scale sheath specimens were used for the experiments. The specimens were positioned to simulate the stays' orientation with respect to the sun.

Figure 2: UT Icing experiment station (Google earth)

Figure 3: Three specimens with different orientations

III. COATING EXPERIMENT INSIDE ICING TUNNEL

In this experiment, the air speed was 8.8 m/s and the cooling unit was turned on until the temperature reached to -5.5 °C, as these conditions were reported as typical conditions for a freezing rain storm. Moreover, the misting system was turned on to simulate freezing rain. This experiment was done for all three coatings as well as the uncoated specimen. For each case three different nozzle sizes, i.e., 40, 42, and 50 microns, were used to simulate different rain droplet sizes. In this report, however, only pictures of the 40 microns nozzle size will be presented. The duration of each experiment was 10 minutes [8].Figure 4 shows the specimen before and after 10 minutes for the 40 micron nozzle system for all of the cases. Table 2 summarizes the results of all the experiments.

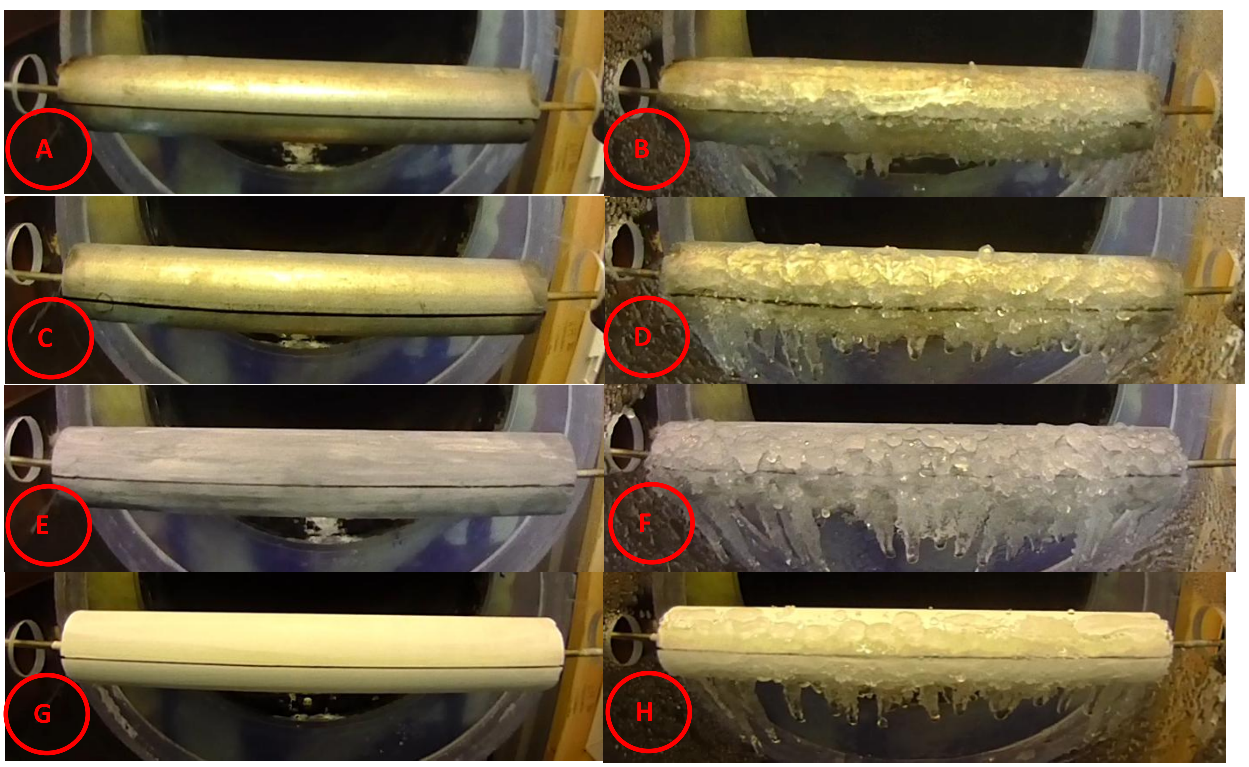

Figure 4: A) Uncoated - 40 Micron - 0:00 min, B) Uncoated - 40 Micron – 10:00 min, C) Aliphatic petroleum distillates with proprietary additives – 40 Micron – 0:00 min, D) Aliphatic petroleum distillates with proprietary additives – 40 Micron – 10:00 min, E) Epoxy polymers, silicate mesh with new melt-point-depressants – 40 Micron – 0:00 min, F) Epoxy polymers, silicate mesh with new melt-point-depressants – 40 Micron – 10:00, G) Fluorocarbon polymer and aliphatic, moisture-cure, three-part polyurethane – 40 Micron – 0:00 min, H) Fluorocarbon polymer and aliphatic, moisture-cure, three-part polyurethane – 40 Micron – 10:00 min

For the coated specimen experiment, three different coatings were used: the aliphatic petroleum distillates with proprietary additives (Coating 1); epoxy polymers, silicate mesh with new melt-point-depressants (Coating 2); and fluorocarbon polymer and aliphatic, moisture-cure, three-part polyurethane (Coating 3). In the case of aliphatic petroleum distillates specimen, the water began to show on the specimen's surface as small droplets, then these smaller droplets combined together forming bigger droplets that moved to the top and the bottom of the specimen. The frozen droplets continued to accumulate, covering the whole surface and forming icicles due to gravity. The thickest part of the ice approximately 10 mm. Similarly, for epoxy polymers and fluorocarbon polymer the same process occurred. However, the sizes of the water droplets on the specimens were smaller, and the icicles became longer and oriented downstream. The thickest part for the epoxy polymers was 10 mm, while the thickest part for the fluorocarbon polymer was 8 mm.

Table 2: Approximated ice thickness comparison of coatings and droplet sizes [1][8]

Coating / Droplet Size	None	Coating 1	Coating 2	Coating 3
40 micron	6.5 mm	10.0 mm	10.0 mm	8.0 mm
42 micron	5.5 mm	6.5 mm	6.5 mm	9.5 mm
50 micron	5.0 mm	6.5 mm	5.5 mm	9.5 mm

As can be seen from the table, none of the coating types prevented ice from accumulating. Instead, the ice accumulation became larger. The reason for this situation was the rapid freezing of the water droplets on the specimen's surface. Additionally, the surface of the ice on the specimen was uneven which trapped water and increased the freezing rate. The table shows that the smaller the droplet sizes, the higher the ice accumulation except for coating 3 which may be due to the different chemical composition of the coating.

IV. COATING EXPERIMENTS AT THE ICING EXPERIMENT STATION

The aliphatic petroleum distillates with proprietary additives was selected for testing on a full scale stay because it is clear and will not affect the color or shine of the stays. The coating was applied to one side of half of the specimen, then a mist of water was sprayed onto the entire specimen. The coating caused water to bead into small droplets. Due to the brushed surface of the sheath, small water droplets did not roll and/or blow off the coated surface, but rather suddenly turned to ice. Figure 5 shows the stay before and after the mist was sprayed[8].

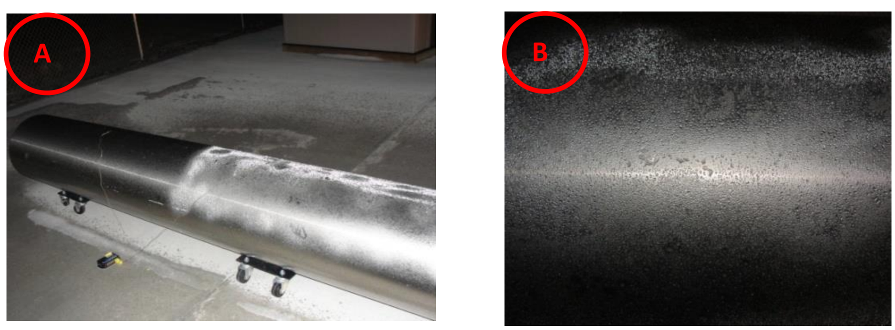

Figure 5: A) Aliphatic petroleum distillates with Proprietary additives Sprayed on half of the Specimen, B) Water Droplets due to aliphatic petroleum distillates with Proprietary additives

Therefore, it can be concluded that after conducting the coating experiments in both laboratory and field, the build-up of ice was not be prevented. Another concern was that the coating tested outdoors developed a gummy appearance on the stays after one month.

V. OTHER TECHNOLOGIES

A. Thermal de-icing/anti-icing (internal heating)

The VGCS stays are hollow with the structural elements occupying roughly 50% of the internal volume, therefore, it would be possible to blow hot air up the stays. To test this idea, internal heating experiments were conducted with a 70,000 BTU forced air space heater as a heat source.

A de-icing and an anti-icing experiment were conducted. For the de-icing experiment, the stay had a 12 mm thick layer of ice accumulated and hot air was blown inside the pipe until the ice melted. Figure 6 shows the melting pattern in the thermal de-icing test. Results of this experiment showed that the heating system successfully melted the accumulated ice without shedding.

The second test was an anti-icing thermal experiment. Initially, the stay was clear with no ice accumulation and it was heated just above freezing, then a mist of water was sprayed onto the specimen. Results showed that after a period of time ice began accumulating on the stay, which is shown in Figure 7.

Figure 6: De-icing Pattern in Thermal Test

Figure 7: Accumulated Ice in Anti-icing Thermal Test

It was found that the hot air was effective in de-icing, but not in anti-icing where the ice still accumulated, which means that more heat is needed to prevent ice from accumulating. Also, the cost for heating a large bridge would be too high[8].

B. Fluid Chemical De-icer

Experiments were conducted using chemicals to determine the efficacy as anti/de-icing technology and also the effect on the stay appearance. The material used was an organic based fluid made of refined molasses carbohydrate, NaCl, CaCl2, KCl, and MgCl2, and the efficacy of the chemical for de-icing of pavements was proven by ODOT[9]. Similar to the internal heating technique de-icing and anti-icing experiments were conducted. For the de-icing chemical experiment, a 1/8 inch thick layer of ice was accumulated on the specimen, and then the fluid was dripped onto the ice layer through a drip tube system. As shown in Figure 8, the chemical was only able to melt down a narrow rivulet through the ice due to its low viscosity [8]. For the anti-icing chemical experiment, the fluid was applied with a manual sprayer on half of the specimen and a mist of water was sprayed onto the specimen to see the efficacy of that anti-icing strategy. Figure 9 shows how ice accumulated on the specimen in the presence of the chemical. This chemical could neither prevent the ice from accumulating nor remove existing ice.

Figure 8: Drip Tube System used in Chemical De-icing Test

Figure 9: Formation of Ice in Chemical Anti-icing Test

VI. REAL TIME MONITORING SYSTEM (DASHBOARD) AND SENSOR DEVELOPMENT

The results showed that none of the technologies were suitable for application on the bridge. Thus, an automated real time monitoring system was built to observe the conditions on the bridge. The dashboard shows data from the sensors (stay temperature, ice accumulation, precipitation, solar radiation) that have been set up on the bridge. In addition, the dashboard shows data that were gathered from local airports and Road Weather Information System (RWIS) stations. An algorithm was developed based on the weather data that were derived from the bridge. This algorithm allows ice accumulation, ice shedding, and clear conditions on the bridge to be identified[1][2]

Figure 10, a screen shot of the dashboard, shows various tabs that allow the operator to view data in many ways. The Dashboard tab, which is the primary tab, provides the current status of VGCS stays with a speedometer-like indicator, a legend of the indicated state of transition, and a running history of the last 48 hours of recorded icing conditions. The Map tab shows weather data at locations where the weather stations exist. The History tab shows records of the weather stations and sensor readings, and finally the Documentation tab shows information about the accumulation, shedding algorithms, and criteria[1][2]. This information will help the operators in monitoring the bridge status and assist them in making the right decision to protect the motorists.

Furthermore, two new sensors have been developed, i.e. ice presence and state sensor and ice thickness sensor. The ice presence and state sensor is a resistance based sensor that is used in detecting the state of the water on the stay or if it is clear. This sensor is very essential in detecting ice accumulation and shedding events. The ice thickness sensor is used to measure the thickness of the ice on the stay by utilizing a laser and camera. The camera is used in detecting the line generated by the laser. By taking pictures during an event, the thickness can be measured with the aid of image processing software. These sensors have been tested successfully both in the lab and field, and will be deployed on the VGCS in 2015.

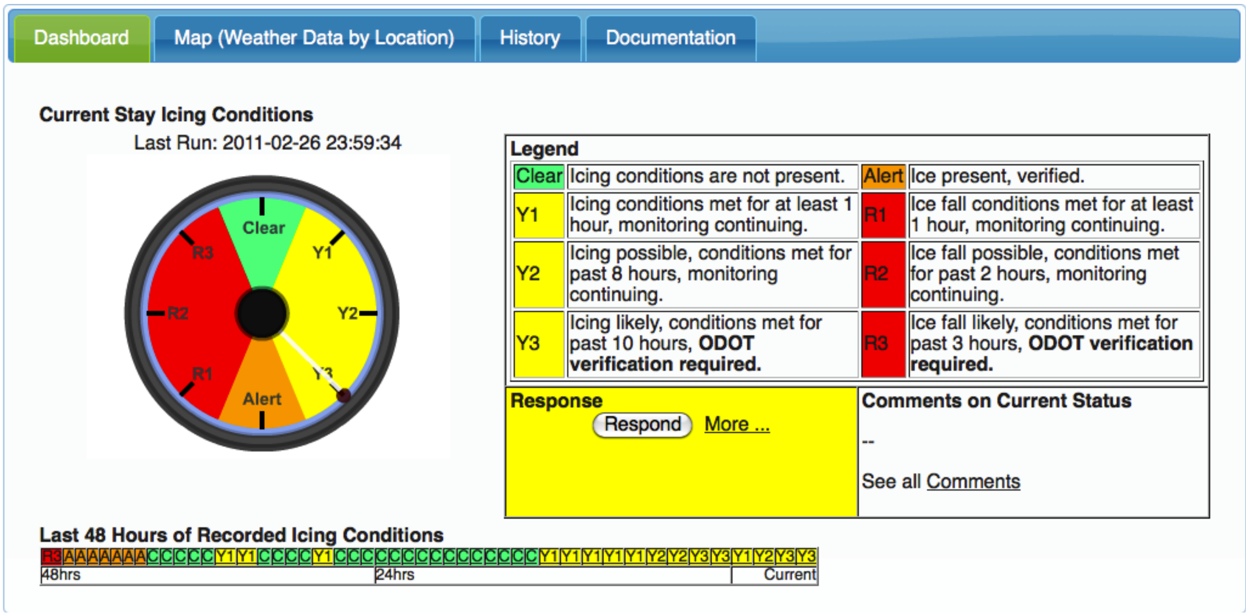

Figure 10: Screenshot of dashboard tab of the monitoring system[10].

VII. CONCLUSION

Three anti-icing/de-icing techniques - coating, chemicals, and hot air - were examined. None of these techniques were appropriate for implementation on the VGCS due to the lack of efficiency in preventing icing, high cost, altering the aesthetic features of the stay, or due to various environmental concerns. An automated real time monitoring system was developed in order to obtain the current conditions of the stays, which will assist the operator in the decision making process based on the information that resulted from the developed algorithms. Moreover, two new sensors were developed, ice presence and state sensor and ice thickness sensor, in order to detect the ice accumulation and ice shedding events, and measuring the ice thickness on the stay. This measured data can be added to the dashboard in order to give precise information to the operator about the stay conditions

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