A comparison of anti-ice and anti-snow coatings performances: laboratory and field testing

Marcella Balordi[1], Andrea Cammi[1], Cristina Chemelli[1], Piero Marcacci[1], Giovanni Pirovano[1], Giorgio Santucci de Magistris[1,2]

[1] *RSE/ Ricerca sul Sistema Energetico, Milano, Italy*
[2] *Università degli Studi di Pavia/ Dipartimento di Chimica, Pavia, Italy*

cristina.chemelli@rse-web.it, marcella.balordi@rse-web.it, pietro.marcacci@rse-web.it, giorgio.santucci@rse-web.it

Abstract— **Anti-icing and anti-snow coatings represent a possible strategy to mitigate the ice accretion on overhead power line conductors and ground wires. Coatings are designed following different strategies, for example low surface energy organic or inorganic compounds or super-hydrophobic hierarchical textured structures. In this work, several aluminum alloy conductor and guard wires samples were prepared with different coatings, which include commercial varnish, tapes and hierarchical structured surfaces prepared in the laboratory. Sandblasting treatments were also done to modulate the micro-roughness of the samples, as well as different application and curing methods. Characterization of sample wettability and ice adhesion strength were carried out in laboratory at room and low temperatures. Anti-snow behaviour was studied in two sites the Italian Alps, during six dry and wet snow event with temperature close to zero Celsius. The research is carried out in the frame of an active collaboration with TERNA (the Italian TSO) and some conductor's manufacturers and varnish producers. The testing activity is important to get a selection of ice-phobic coating to be applied for testing on operative HV lines, in areas exposed to wet-snow risk.**

In order to qualify the anti-snow behaviour, two qualitative figure of merit are proposed. One describe the fraction of surface covered by snow in a given time interval and the second represent the maximum accretion load reached by the sample with respect to the reference. Results of laboratory and field testing are compared and discussed. Results demonstrate that laboratory tests and outdoor results are complementary and it is necessary to consider them both to investigate correlations between the wettability and anti-snow behaviour. Field testing indicate that several different mechanism of snow adhesion and sleeve shedding can play as a function of coating structure and composition and environmental parameters.

Keywords— **coating, anti-snow, super-hydrophobic, ice adhesion, field test**

I. INTRODUCTION

The development of anti-icing and anti-snow coatings is one of the possible strategies to mitigate the ice and snow accretion on overhead power line conductors and ground wires. Coatings are designed following different strategies, for example low surface energy organic or inorganic compounds, super-hydrophobic hierarchical textured structures, slippery structures and many others [1]-[5]. Nevertheless, a clear comprehension of their behaviour against ice and snow is still under discussion and classification and qualification procedures are not established yet [6], [7]. In order to obtain clear indications for coating extensive applicability on real scale over-head grid structures, the coating performances, their durability and reliability need to be assessed both in laboratory and under real climatic conditions, identifying relevant parameters and figure of merit.

Ice and snow accretion phenomena occur in different climatic conditions, where temperatures, air humidity, precipitation type, wind speed and other parameters can vary in a very wide range of values. Consequently, accreted masses from blue ice to rime, dry snow, wet snow etc. can differ in terms of density, liquid water content, toughness and adhesion properties. At present, coatings able to reduce ice/snow accretion in any circumstance does not exist, and a possible mitigation strategy should disentangle different solutions for each climatic case, tailoring the coating functional properties with respect to the specific application. In Italy, the most severe problems are caused by wet snow that accretes in the form of heavy sleeves on conductors and guard wires [8]. Typical temperatures for this phenomenon are slightly above zero Celsius degree and snow density may reach 350 Kg/m^3. Just a couple of degree below, snow is dry and much less dense, sticky and dangerous. For this reason the experimental activity described in this paper is aimed at assessing the coatings behaviour in the temperature range around zero Celsius under real snowing events, supported by testing and characterizations carried out in the laboratory.

In order to give a graphical representation of the behaviour of each sample during the snowing event, a methodology was developed that finally lead to some figures of merit intended to qualify the coating behaviour.

This works aims at illustrating as both indoor and outdoor characterizations are complementary and necessary to boost a deeper comprehension of snow adhesion phenomena on surfaces having different properties and structures. In fact, experimental results show different behaviour of coatings, that suggest that more than one mechanism of adhesion and shedding participate in different measure to the behaviour of a specific coating, also varying as a function of the temperature.

II. MATERIALS AND TREATMENTS

A. *Preparation of the samples*

Aluminum alloy substrates in the form of plates, rods and real conductor and guard wire pieces were used. Seven different surface treatments or coatings were applied, as reported in Table I, while some reference sample were left in pristine conditions (sample #1). Some coatings were formulated and applied in our laboratory (#2-5) as described in the following, while others have been prepared by applying one commercial PTFE ribbon supported on glass fibre (#6), one commercial hydrophobic varnish (#8) and prepared by a conductor producer with a proprietary process (#7).

In particular, for what concerns laboratory developed coatings (samples #2-5), the specimens were cleaned before the coating application with basic soap, rinsed in ultrasonic bath for 10 minutes with acetone and dried under nitrogen flux. Some of the aluminium surfaces were treated to produce different micro-scale roughness by means of sand-blasting using angular corundum or by shot-peening using glass microspheres [9]. In some cases, a nanometric acicular oxide (pseudo-boehmite) was accreted on the surface by a simple treatment in boiling water for 30 minutes [10],[11]. Finally, samples were dip-coated with Dynasylan® SIVO CLEAR EC fluoroalkyl silane (SIVO) or with Evonik Dynasilan alkylate (ALK) purchased from Evonik and finally dried at 70°C for 1 hour, as described in [12],[13] and reference cited therein.

Sample #6 was coated with a glass fibre supported PTFE tape, wrapped as a spiral around a cylindrical sample (conductor piece or guard wire piece) leaving some fraction of the surface uncoated, as described in [14].

Sample #8 was prepared applying NUSIL™ R1009 varnish, following the curing procedure indicated by the producer.

TABLE I: SAMPLE PREPARATION

Sample #	Type of coating	Surface microstruct.	Surface nanostr.	Final hydrophobic coating
1	None (REF Sample)	As grown	None	None
2	Nanostructured	As grown	Boehmite	ALK
3	Hierarchical hydrophobic	Sand blasting	Boehmite	ALK
4	Hierarchical super-hydrophobic	Shot peening	Boehmite	SIVO
5	Hierarchical super-hydrophobic	Sand blasting	Boehmite	SIVO
6	Tape	None	None	PTFE Tape + glass fibre support
7	Producer1	Unknown	Unknown	Unknown
8	Commercial varnish	None	None	NUSIL R1009

III. . Laboratory characterization

B. *Hydrophobicity characterization at room and low temperatures*

The static water contact angle (WCA) was measured using a 2 µl water drop at 23°C. WCA measurements at low temperature were conducted by means of a Peltier chamber, decreasing the temperature to -4°C and depositing the drop on the cooled samples. Contact angle hysteresis (CAH) was calculated as the difference between the advancing and receding contact angles, measured increasing and decreasing the volume of a water drop. The roll-off angles (RO) have been measured with an home-made tilting table equipped with a goniometric scale, using a 20 µl drop of water. To measure the roll-off angles at low-temperature the tilting table was inserted in a climatic chamber.

C. *Shear stress ice adhesion tests.*

Ice adhesion forces were evaluated by shear stress analysis performed with a home-made apparatus, equipped with an electromechanical testing system INSTRON 4507. Aluminum alloy bars (diam. 12 mm) were used as test samples, frozen in an aluminum alloy mould, in 40 ml of deionized water at -19 °C for at least 8 hours and then pulled from the ice at a speed of 4 mm/min, as described in [13]. The adhesion reduction factor (ARF) was calculated as the ratio between shear stress of bare aluminum alloy and of the coated sample.

IV. Field characterization

D. *Testing under real snowfall conditions*

Outdoor testing were conducted in two sites located on the west region of Italian Alps (WILD Station, Vinadio, Piedmont) and on the east side of the Alps (Malga Ciapela, Veneto), thanks to the collaboration with TERNA and a conductor manufacturer, as described in detail in [15]. Three kind of samples were exposed, namely conductor specimens (C) 31,5 mm diameter and 1.5 m long and guard wires specimens (gw) 9.5 mm diameter and 15 m long in Vinadio; real service guard wires (GW) 9.5 mm diameter and 140 or 80 m long, in Malga Ciapela station.. Monitoring facilities and instruments mounted in the two sites are thoroughly described in [15].

E. *Evaluation method of field performances*

The performances of exposed samples have been observed and recorded during the past winter seasons. Some meaningful snow events (in terms of precipitation amount) occurred in February and April 2019 and are summarized in Table II. For the analysis reported in this paper, we recorded and analyzed the images collected from 5 cameras every 15 minutes. Related temperatures, precipitation rates and data from one load cell installed on a reference sample in Vinadio were simultaneously recorded.

The behaviour of the conductor and guard wires specimens exposed to snow events in the test facilities are observable from the acquired images, as for example in figure 1, in which samples showing different portion of surface covered by snow and different sleeve dimensions can be noticed.

In order to give a representation of the behaviour of each sample during the snow event, each image was analysed and a coefficient was assigned to each sample expressing the fraction of the surface that appeared covered by a snow layer, independently on the diameter of the snow sleeve. In this way, the operator was asked to give a qualitative number in the range 0-1 (**cov**) to express if the wire is totally free of snow (zero value), or completely covered (1) or any intermediate value. This approximate evaluation was repeated by other researchers giving very similar results.

The estimated coverage values (**cov**), the temperatures, the precipitation rates and cumulated precipitation data were collected in a table with reference to the time.

A first figure of merit to describe sample performances can be calculated from the coverage data, as the sum of the **cov** values in each time slot and normalizing the total with respect to the reference sample. This relative coverage number (**RCov**) is lower than one for samples performing better than the reference, or greater for samples that perform worse.

The load cell mounted on a conductor reference sample in Vinadio gave the weight of the accreted snow sleeve every 15 minutes. An Estimate Relative value representing the Load of snow accreted at the time n (**ERL$_n$**) was also calculated from the coverage (**cov**) and the precipitation rate (**PR**) data, adding the load already present on the sample at time n-1 or subtracting the amount that shed as follows:

$$\mathbf{ERL_n = cov_n{*}PR_n + ERL_{n-1}} \qquad (\text{if } cov_n >= cov_{n-1})$$

$$\mathbf{ERL_n = cov_n{*}PR_n + ERL_{n-1}/cov_{n-1}{*}cov_n} \quad (\text{if } cov_n < cov_{n-1})$$

TABLE II SNOW EVENTS

SNOW EVENTS	A	B	C	D	E	F
Site	Vinadio	Vinadio	Malga Ciapela	Malga Ciapela	Malga Ciapela	Malga Ciapela
Date	1-2 Feb 2019	2-3 Feb 2019	1-2 Feb 2019	2-3 feb 2019	04-apr-19	05-apr-19
TEMP MIN (°C)	-4.6	-0.7	-1.5	-1.8	0.0	0.0
TEMP MAX (°C)	-0.7	3.4	1.3	1.1	1.5	0.1
TEMP AVE (°C)	-2.7	0.4	0.1	-0.1	0.2	0.1
Cumulated precipitation (mm water equiv.)	51	12.6	40	15	20	70
PREC RATE MAX (mm/hr)	5.6	6.4	3.4	2.4	7.4	7.8

.Fig. 1 Example of image collected in Vinadio during a snow event. Several guard wires (gw) samples and their snow coverage are visible.

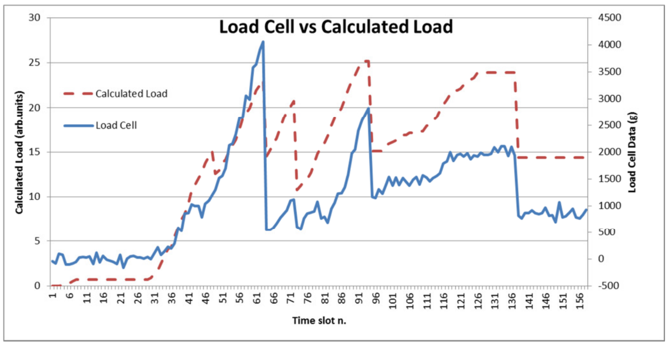

Fig. 2. Load cell data compared to the ERL of the reference sample as a function of time during the snow event A.

In the following figure 2 the data from the load cell are compared to the calculated load profile ERL for the same reference sample. It can be observed that the trend of the loading and shedding phases are in good agreement, while the relative values differences can be accounted for considering the density of the snow that was very low at the beginning of the event and increased after few hours.

As the snow density is the same for all the exposed sample, the calculated ERL is considered to give a reasonable qualitative figure of the accreted sleeves on the samples. In figure 3 the profile of ERL for four samples during snow event C is shown. Although the calculation is qualitative and approximate, the differences in the sample behaviour are very clear and unambiguous.

Basing on these considerations, a second figure of merit can be obtained from the ERL values, taking into account the maximum value reached by each sample in a given event relatively to the reference sample (Maximum Relative Load, MRL).

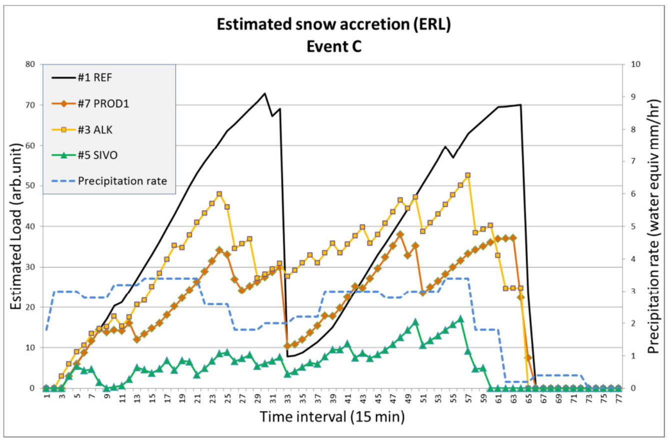

Fig. 3 ERL graphs of four samples during event C in Malga Ciapela. Precipitation Rate data are also reported (on the right axis).

V. Results and Discussion

F. Laboratory characterization results

In Table III hydrophobicity results and ARF data are summarized for all the samples.

Form WCA room temperature data, samples can be grouped in three classes: *i*) super-hydrophobic (#4 and #5), *ii*) hydrophobic (#6,#7 and #8), and *iii*) weakly hydrophilic (# 2 and #3), related to the chemical finishing of the surfaces, respectively SIVO, PTFE (or similar compound) and ALK.

At low temperature, WCA reduces noticeably for all samples as expected [16], leading sample #7 to lose hydrophobicity.

Hysteresis data are spread in a quite wide range, where sample in group *iii* perform better. At low temperature all data worsen, except for sample #6 that improves his CAH datum. Roll off angles are better for samples in group *i* at room temperature, but at lower temperature groups are no more clearly defined. ARF data show best performances for samples #2 and #8, followed by #3 and #4. ARF data are not available at present for sample #7.

From the laboratory characterization data it is an hard task to predict sample behaviour during snow events. For example, sample #2 is the worst for WCA but it has excellent hysteresis and is the best in ARF. Samples #4 and #5 have super-hydrophobic WCA but moderate ARF, although hysteresis is rather good at room temperature, but not at low temperature. Sample #6 shows quite mediocre data, so that one could expect a poor field performance, that will not be the case.

TABLE III Laboratory characterization results

SAMPLE	WCA (°)	CAH (°)	RO (°)	WCA (°)	CAH (°)	RO (°)	Shear Stress ARF
	Temp. 20°C			Temp. -4°C			
#1	93.5						1.0
#2	86.7	1	7	84	3.5	41	31.5
#3	89.0	2.9	10	84.1	4.8	19	14.8
#4	169.6	2.6	1.3	141	17	17	11.3
#5	170.7	5.6	1	142	23	>90	8.3
#6	111.6	51.7	39.3	95.8	21.7	87.7	1.9
#7	101.1	21.6		80.8			
#8	117.0						23.5

G. Field testing results

In Table IV and Table V we report the relative coverage **RCov** and estimated maximum load **MRL** with respect to the reference sample respectively for events occurred at Vinadio and at Malga Ciapela. Data refer to the six snow events cited above (Table II).

In Vinadio (events A and B) the sample exposed were conductor pieces 1.5 m long and guard wires 15 m long. Events C-F occurred at Malga Ciapela where four service guard wires 80 and 140 m long were installed. Moreover, event A is a typical dry snow event, with temperatures well below zero. The other events are wet snow event or mixed dry/wet, depending on the air temperatures.

Data reported in Table IV show that samples #5, # 4 and #6 perform better than other samples in event A (dry snow). Sample # 6 (PTFE ribbon) showed rather poor hydrophobic qualities but it behaves well in field testing, in particular during dry snow events. Camera images show the tape surface often clean from snow. Samples #2, #3 show the best behaviour in terms of coverage during event B (wet snow), where #4 and #5 show minor MRL values. Sample #7, exposed only in event A, show the worst performances in Vinadio, but it behaves quite well in Malga Ciapela (Table V). Sometimes, samples perform worse than the reference sample. Data related to event A and B are, in summary, rather scattered, differences can be noted among type C or type gw specimens and it is difficult to recognise best performing categories, even if some important correlation with temperature, precipitation rate and wind can be more deeply analysed.

TABLE IV Sample performances in Vinadio

SAMPLE	type	EVENT A		EVENT B	
		RCov	MRL	RCov	MRL
#1	gw	1	1	1	1
	C	1	1	1	1
#2	C	0.75	0.78	0.97	0.67
#3	gw	1.02	0.94	1.13	1.21
	C	0.75	0.69	0.9	0.52
#4	C	0.45	0.61	1.06	0.34
#5	gw	0.54	0.62	1.47	0.71
	C	0.35	0.87	1.04	0.31
#6	gw	0.48	0.53	1.41	0.63
	C	0.77	0.89	1.09	0.6
#7	gw	1.08	1.57		
#8	gw	1.07	1.3	1.32	1.76

TABLE V Sample performances in Malga Ciapela

SAMPLE	type	EVENT C		EVENT D		EVENT E		EVENT F	
		RCov	MRL	RCov	MRL	RCov	MRL	RCov	MRL
#1	GW	1	1	1	1	1	1	1	1
#3	GW	0.85	0.72	0.82	0.62	0.88	0.95	0.34	0.32
#5	GW	0.44	0.23	0.65	0.49	0.54	0.59	0.08	0.09
#7	GW	0.74	0.52	0.77	0.57	0.78	0.77	0.61	0.6

On the contrary, in Table V data from events C to F are quite homogeneous. In fact, sample #5 is always the best performer, sample #7 is the second best except for event F, and sample #3 is the third of the list, but undoubtedly better than the reference sample, which is always the worst. In figure 3 the ERL values calculated for the four samples during event C are shown. It can be noticed that sample #5 shows very frequent load and shedding phases, corresponding to frequent detachment of fragment of the sleeve from the wire. Instead, samples #3 and #7 seems to shed the sleeve upon reaching a “critical” weight.

Some consideration can be drawn from the collected data.

Samples #4 and #5 (super-hydrophobic SIVO) perform well in field test, despite a poor hysteresis and roll-off angles at low temperature. Data of event A and B seem to suggest a better behaviour under dry snow precipitation. In Malga Ciapela sample #5 performs very well also with temperature slightly above zero and under abundant snow fluxes. Coverage data suggest that this kind of coating allows the wire to remain free of accretion for longer period with respect to the reference and consequently the accreted sleeve is smaller, that seems to be related to the high WCA angles. During event E and F, reported in figure 4, a noticeable delay in the accretion on wire #5 is clearly visible, being more than one hour for event E and 2.5 hours for event F. Anyhow, events E and F show dissimilar load accretion for all the samples. Question arise on a possible influence of the rain fall before the beginning of snow event E, that could have wetted the surfaces.

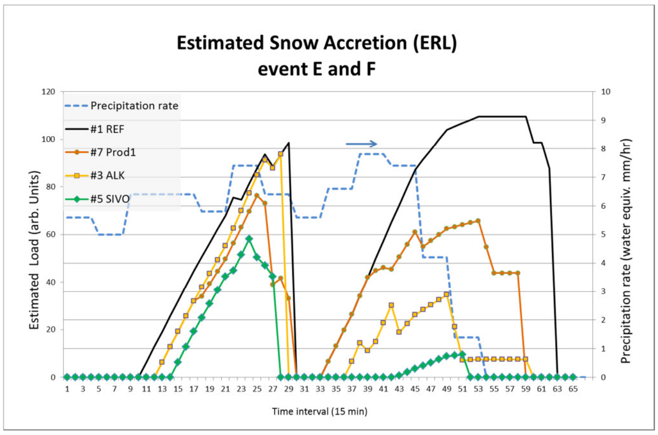

Fig. 4 ERL graphs of four samples during events E and F in Malga Ciapela. Precipitation Rate data are also reported (on the right axis).

Samples #2 and #3 (structured surfaces ALK) have noticeable field performances despite poor WCA data. Some observations suggested better performances under wet snow. Data show better behaviour in terms of accreted load with respect to coverage, indicating that this coatings does not delay the accretion of the first snow layer (as sample #5) but rather it allows an early shedding of the sleeves, that fall when reaching minor weight with respect to the reference. This behaviour is coherent with the high ARF obtained in laboratory tests.

Sample #7 (Producer1) perform much better in Malga Ciapela with a 140 m long guard wire than in Vinadio with the same wire only 15 m long. It’s worth noting that the wires have been cut from the same span. It is probable that with real scale spans, wind and vibrations are more effective in causing shedding, so that coatings efficacy are more clearly visible, for all samples.

Data suggest that the accretion and shedding mechanisms could be different for sample #5 with respect to sample #2, #3 and #7.

Sample #8 showed good performance during the preceding winter season 2016-2017 that unfortunately is not confirmed in these recent events. Reasons for this behaviour are under examination.

VI. Conclusions

Several samples with different coatings for anti-snow protection were prepared and tested both in laboratory and exposed to real snow event in two sites in the Italian Alps.

Laboratory characterization results include water contact angle, hysteresis and roll-off angles measured at 20°C and at -4°C. All the hydrophobic characteristics decrease at lower temperature. Shear stress test have been performed and Adhesion Reduction Factors were calculated.

Field performance of exposed samples have been analysed observing camera images taken every 15 minutes during the snow events. Air temperature and precipitation rates have also been recorded. Six events are considered for the present analysis.

In order to obtain a qualitative visualization of samples performance during precipitations, a method is adopted to calculate two figures of merit, one related to the snow coverage of the sample surface and the second related to the maximum load of the accreted sleeve with respect to the reference samples. The qualitative calculation of the accreted load was based on the coverage and the precipitation rate. The calculated relative load was compared with data obtained from a load cell mounted on a reference sample, demonstrating a reasonable agreement of the estimated relative load.

A general observation is that service guard wires with real scale length show more clear and homogeneous results than short specimens as those mounted in the WILD station in Vinadio.

The experimental evidence is that different coating typologies can behave differently upon temperatures variation of few Celsius degree, under wet or dry snow. Moreover, the mechanism of mitigation can be of different kind, for example by retarding the adhesion of the first snow film or rather accelerating the shedding of the accreted sleeve.

Comparison of laboratory and field data demonstrate that the behaviour of coatings in real conditions is not predictable straightforward from laboratory characterization results. Or, at least, there is no specific properties that is directly related to anti-snow functionality, be it contact angle, hysteresis or ARF.

On the contrary, the analysis of field data can suggest a possible mechanism on which a coating can operate and laboratory data can support the investigation and the understanding of the phenomena. The collaboration with important stakeholders as the Italian TSO TERNA and conductors and coating producer is of fundamental importance to the research activities allowing RSE to access testing location, materials and industrial scale processes.

Further analysis of laboratory and field testing data can be performed searching for correlation with temperatures, wind, air humidity, snow density and other variables, as for example the fact that the wire surface were already wet at the beginning of the snow event, due to a previous raining. Comprehension of snow adhesion phenomena is still an open issue.

ACKNOWLEDGMENT

This work has been financed by the Research Fund for the Italian Electrical System in compliance with the Decree of Minister of Economic Development April 16, 2018. The authors would like to thank Mrs N. Belgiovine, Mr S. Capelli, Mr G. P. Carbi, Dr F. Cernuschi, Mrs E. Erbaldi, Mr G. Quinteri, Mr L. Lorenzoni and Mrs F. Tulli for their precious work in laboratory and field testing.

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