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Adhesion of Wet Snow to Different Cable Surfaces

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Abstract—**Cohesion of snow and its adhesion to cable surfaces are the decisive factors for wet-snow shedding from power-line cables. Knowing the adhesive strength of snow is essential to predict when snow will shed and what consequences it will have on the elements of the transmission line. It also appears to be a basic input for simulating wet-snow shedding. Snow adhesion depends on several parameters, among which snow liquid water content and density, and cable surface geometry were examined experimentally. In particular, the adhesion of wet-snow samples to flat surfaces of different roughness, and to stranded cable surfaces was examined in this study. Two series of experiments were conducted to measure shear adhesive strength as well as tensile adhesive strength of snow. Shear adhesive strength was measured with a centrifuge adhesion test device where a snow sample was placed on a beam, which was then rotated with increasing angular frequency until detachment, the angular frequency at detachment being proportional with shear adhesive force and strength. The tensile adhesive tests were carried out with a material test machine on a semi-spherical snow sample. The sample was compressed slowly at a constant speed until it reached a predefined compressive force limit, and then a tensile load was applied until the detachment of snow. The main observations showed that adhesion was strongest for a critical value of liquid water content, that shear adhesive strength was greatest on stranded cable surfaces, and that tensile adhesive strength was weaker on stranded than on flat cable surfaces.**

I. NOMENCLATURE

F_c	centrifugal force	(N)
r	radius of the beam	(m)
m	snow mass	(kg)
ω	angular velocity	(rad/s)
D	plate diameter	(m)
S	tensile adhesive strength	(N/m^2)
F_t	tensile force	(N)
A	contact area	(m^2)

II. INTRODUCTION

A. Problem

Wet snow containing free water accretes and adheres easily to cables and conductors, and may cause problems to the transportation and distribution of electricity. Thus, the need for reliable transmission promotes the importance of snow adhesion studies.

Snow accretion grows on overhead wires due to the adhesive force between the surface of the wire and the snowflakes, and to the cohesive force between the snowflakes themselves. The main mechanisms which are dominant in wet snow are as follows: (a) capillary action due to liquid water content, and (b) coherent force between ice particles and water formed through the metamorphism of snowflakes [1]. When the wind forces and/or gravitational forces exceed the cohesive and capillary forces, snow sheds from the wire. Studying snow shedding is essential for the transmission line design because it helps to predict how long snow stays on cables causing vertical and /or longitudinal load, and when it sheds.

B. Previous Research

1) Snow Shedding

Field observations of natural wet snow shedding from a cable are rare and not well documented. Shedding occurs following an increase of the snow liquid water content (LWC) governed by the thermal equilibrium of the snow sleeve. The LWC of the snow matrix controls the strength of the capillary forces and promotes contact between ice granules leading to ice bonding [2]. At low LWC, air gaps expand through the microstructure, and water distribution in snow is considered to be in the pendular regime. At higher LWC, however, where free water becomes continuous through the pore space, water distribution in snow is considered to be in the funicular regime. In the pendular regime, wet snow exhibits increasing cohesive strength as its LWC increases, but when the transition to the funicular regime occurs, the cohesive strength of wet snow is reduced with increasing LWC. The exact LWC at which shedding occurs is difficult to predict, as it depends on snow density, air temperature, wind velocity, and snow fall intensity [3]. The range of LWC values reported at the time of shedding varies between 20% and 40% by mass according to [2] and [4] whereas higher values, between 35% and 50%, were observed in [5], [6], [7]. The LWC was expressed as the mass of the liquid water divided by the total mass of wet snow as a percentage (% LWC by mass) in these studies, a practice which is adopted in the present paper.

Snow was observed to shed in-situ at first at the axial growth area, which is close to the towers where cable rotation is prevented [8]. In case of cylindrical sleeve growth, snow sheds partially in segments up to 30 m, and the total partial shedding occurs within 5 to 10 min [5].

During wet snow events, there are successive cycles of accretion and shedding (saw-tooth loading), whose frequency may be increased by Joule heating [9]. It was observed that snow sheds in a random and partial manner from phase conductors, whereas from overhead ground wires snow shed in an unzipping manner causing large oscillations [5]. Random and unzipping shedding may also co-exist, which is known as mixed mode.

Wet snow subjected to overnight freezing is unlikely to shed naturally by solar radiation, but it can shed by sublimation or melting when temperature is above the freezing point of water, as is the case for rime ice and glaze ice [10].

Although the above researchers have studied wet snow shedding and its relation with LWC, they did not examine snow adhesion.

2) Tensile Adhesion Tests on Snow

The compressive strength of snow is very high comparing with its tensile strength, which is about 0.2% of the former. Specimens of polar snow tested at Greenland failed at an average unconfined compressive strength of 302 psi (2.1 MPa) at -25°C, while those tested at Cold Regions Research and Engineering Laboratory (CRREL) failed at 384 psi (2.7 MPa) at 3°C to 5°C warmer temperature [11]. Thus, the tensile strength is a dominant parameter for assessing the failure of snow. The main factors that affect tensile strength are snow temperature, density, and microstructure parameters [12]. The tensile adhesive force of wet snow was measured using a material test system (MTS) machine [13], and the highest tensile adhesion strength was observed when the free water content of snow was around 12-16%. Wakahama et *al*. [13] also studied snow adhesion to different materials like aluminium, teflon, glass, vinyl, and rubber, but did not change the surface roughness.

A conventional technique to measure the tensile strength of snow was used, while the centrifugal technique was examined and its capabilities were shown in [12]. Ballard and Feldt studied the tensile strength also using centrifuge on age-hardened snow [14] whereas Keeler and Weeks [15] conducted the same centrifugal experiments on fine grained snow. Sommerfeld [16] determined the maximum strength envelope for snow as a function of density. Keeler [17] also presented centrifugal tensile experiments on natural snow, while field experiments using large sample sizes were carried out by McClung [18].

The tensile strength of snow is significantly lower than that of ice, with an average of 1.43 MPa in a temperature range from -10°C to -20°C, and it increases with snow density [18], [19]. It was observed that the tensile strength ratio of snow to ice was proportional to the cube of the density ratio of snow to ice.

3) Shear Adhesion Tests on Snow

Many investigations have reported the shear strength of alpine snow, using in-situ shear frame, in-situ shear vanes, and laboratory shear apparatus [20]. These studies found that shear strength was associated with snow density rather than snow temperature or grain size. Mellor [21] studied the relation between snow density and shear strength for only dry bonded snow, and he mentioned that snow shear strength increased with the increase of snow density.

4) The relation between tensile strength and shear strength

Earlier studies by Keeler and Mellor [20], [21] discovered that the ratio of tensile strength to shear strength usually exceeded 5. This ratio is very high, since the tensile strength does not exceed twice the shear strength for most other materials. The reason of this extraordinarily high ratio is that the shear frame and vane tests significantly underestimate the shear strength as reported by McClung [18]. Roch [22] tested alpine snow in tension and shear using large samples of comparable dimensions, and he found that the relation between tensile strength and shear strength was close to 2.

The main objective of this study is to determine wet snow adhesion to cables depending on snow characteristics and cable surface. The shear adhesive strength is measured by a centrifugal machine, and the tensile adhesive strength is obtained by applying MTS. These parameters are essential to study because the tensile and shear strengths of snow are significantly smaller than its compressive strength. This study will discuss the effect of cable surface roughness, snow LWC, and snow density on the shear and tensile strength of snow, which will help to predict under what conditions the snow persists on the cable.

III. EXPERIMENTAL PROCEDURES

This section describes the two sets of experiments which were carried out in this research: shear experiments using the centrifugal machine and tensile experiments using the material test machine.

A. LWC and Density Measurements

LWC and density were measured in both series of experiments. The LWC was obtained by using a Decagon model EC-5 moisture sensor (see Fig. 1). This sensor provides a reading in voltage, which is based on the dielectric constant of the medium. This voltage is converted into volumetric water content using a calibration curve, and the LWC (% by mass) is obtained by dividing the volumetric water content by the snow density.

Fig. 1. EC-5 probe

The density was measured by using a digital balance, as well as a cylinder for shear tests and a semi-spherical plate for tensile tests, both of them of known volume.

B. Surfaces

In the current shear experiments, four types of surfaces were used: super fine surface (which will be called smooth surface in what follows), rough surfaces which are prepared with sandpaper No. 100, and No. 50, and a surface for simulating a stranded cable surface, whereas only three types were used for tensile experiments: smooth surface, rough surface No 50, and stranded surface. Figure 2 shows beam surfaces used in shear tests and plate surfaces used in tensile tests. The surfaces prepared with sandpaper may be described as follows [23]:

- CAMI Grit designation: No. 50 (coarse surface) = average particle diameter 348 µm.
- CAMI Grit designation: No. 100 (fine surface) = average particle diameter 140 µm.
- CAMI Grit designation: No. 400 (super fine surface) = average particle diameter 23 µm.

Stranded cable surface is prepared by using a milling machine resulting in a roughness height (simulates the fiber radius of the stranded surface) of 0.06632 inch (1.68mm) on plates or beams [24].

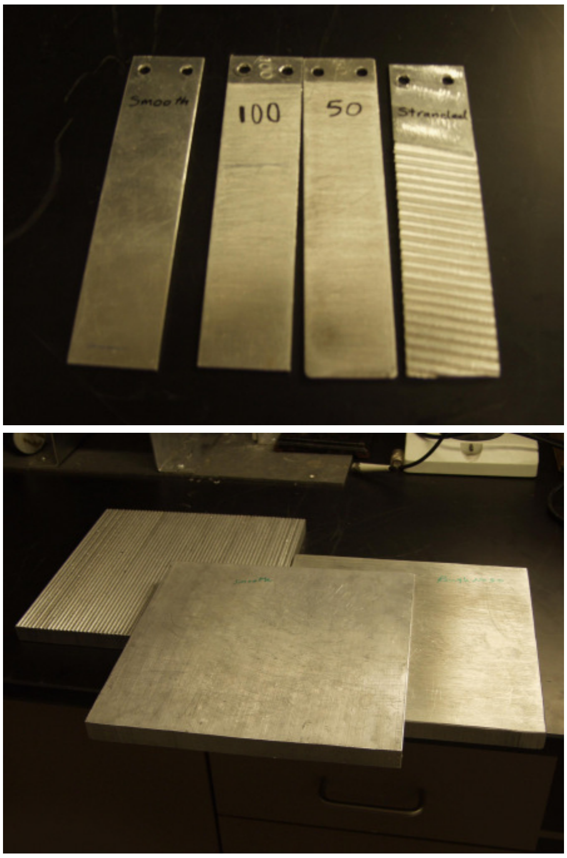

Fig. 2. Beams and plates with different roughness

C. Shear adhesion tests

1) Sample preparation

The following equipment was used in preparing samples for the shear experiments: (i) aluminium beams (140x32x1.5 mm) with different roughness, as shown in Figure 2, and (ii) wet snow mold which can be used in general to simulate wet snow accreted around cables. In the current experiments this mold was used to compress wet snow sample upon the extremity of aluminium beams, for using in centrifuge machine. This method is used in order to achieve the shear adhesive force of accreted snow. The dry snow was stored in a cold room at temperature above 0°C for 30 min or longer in order to obtain wet snow with LWC between 5% and 45%. The obtained wet snow is laid in a semi-cylindrical mold and compacted evenly. Once the bottom half of the sleeve was formed, two beams were used at the sides of the mold, while the top half of the sleeve was compacted. The aluminium beams were separated with snow on their surfaces 20 min later. The snow mass on each beam was 10 g ±10%. The LWC of the snow in the mold was measured immediately after the end of the test, where the snow in the mold was assumed to have the same LWC as the snow on the beams tested in centrifuge machine.

2) Procedures

The advantages of the centrifuge adhesion test (CAT) are that wet snow prepared in a cold room under simulated atmospheric conditions can be used, and that the small snow samples allow us to reach homogenous snow. Additionally, this centrifuge test is economic and rapid.

The snow beams are tested using the centrifuge machine in a cold room (see Fig. 3). All the tests were conducted under constant temperature conditions. However, a variation in cold chamber temperature was observed to be 0 ± 3°C. The beams are rotated with increasing speed from 0 to a maximum, and the shear force is obtained from the angular velocity of rotation when the snow is detached from the beam as follows:

$$F_c = m\,r\,\omega^2 \qquad (1)$$

Fig. 3. The centrifuge machine

D. Tensile Adhesion Tests

1) Sample preparation

The dry snow was stored at room temperature for at least 30 min until it became wet. The LWC of snow was varied between 5% and 45%. At the mean time the cold room of the MTS machine was cooled to 0 ± 3°C. Then, semi-spherical plates with a flattened top (D_{small} = 70mm, D_{big} =165mm) were used for preparing samples for tensile experiments.

2) Procedures

The material test machine (MTS) was used for conducting material tests (tension and compression), which is equipped with as follows:

- Hydraulic closed loop to perform a controlled low to high strain rate creep test.
- Multi-channel data acquisition system to record the output data.
- Confining hydrostatic pressure chamber up to 20 MPa.
- Cooling chamber with a temperature as low as -40°C

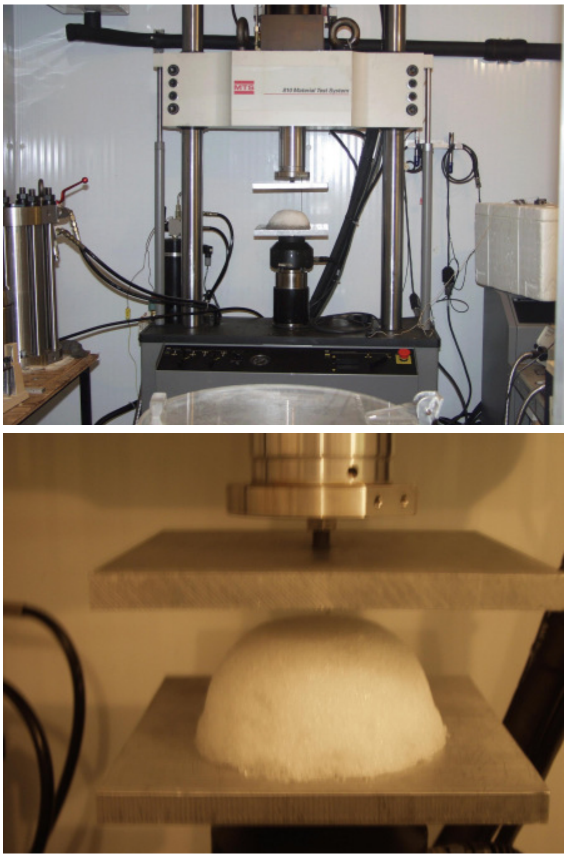

Fig.4. The material test machine

The tensile test procedure is based on the recommendations of Wakahama [13]. The semi-spherical snow sample was slowly compressed from the top by a plate, moving downward at a constant speed of 1mm/min. The compressive force is increased with time, and the motor is stopped at the instance when the force reached 80 N. Although the smaller diameter of the snow sample is 70 mm, the diameter of its contact area with the plate increases up to between 75 and 80 mm during compression; thus, the compressive stress is between 16 and 18 KN/m^2. Then a period of stress relaxation begins, whose duration is selected to be 2:20 min. Finally, an upward motion of the plate is started at the same speed of 1 mm/min. Thus the force is changed from compressive to tensile, and the tensile force increases with time until the plate and the snow sample are separated from each other. The peak of tensile force is recorded at separation. The tensile adhesive strength S is calculated as F_t/A.

V. RESULTS AND DISCUSSION

A. Shear Adhesion Tests

The shear adhesion test results illustrate the relation between shear adhesive strength and snow properties, and also between shear adhesive strength and surface roughness.

More than 180 tests were conducted in order to obtain reliable results; however, average values in each 5% interval for LWC or 100 kg/m^3 for density are presented in the strength – LWC and strength – density graphs. Figure 5 explains the relation between the shear adhesive strength and LWC. It can be observed that the shear strength augments as LWC increases, and then reaches its maximum value at 20 to 25% of LWC for all surfaces. This maximum appears for the highest LWC value for the smooth surface. For higher values of LWC, the shear strength decreases with LWC. It can be concluded from this remark that snow containing a low amount of liquid water has low adhesion to aluminium beams. When free water begins to increase, snow at this stage will be wet and it adheres very strongly. Then snow begins to be transparent and slushy, at this stage it will have low adhesion strength, which goes gradually to zero. With a moderate value of LWC the cylindrical snow sleeve can develop, which cannot be broken easily by vibrations. However, with a very high value of LWC the snow sleeve flows like a viscous liquid, or breaks under gravity effect. The surface roughness also has a very significant effect on adhesive shear strength. The greater the roughness, the greater is the adhesion.

Figure 6 represents the relation between density and shear adhesive strength of wet snow. In general wet snow has a wide range of densities which ranges from 0.1 to 0.9 g/cm^3 [13]. It can be observed that the shear strength increases with density up to a density value ranging from 0.4 to 0.5 g/cm^3. After that, the shear strength decreases at higher values of density. Since snow samples with LWC in the range of 20 to 25% have densities in the range from 0.4 to 0.5 g/cm^3 (see Fig.7), this result may be explained by the same reasoning as that presented in the previous paragraph. Furthermore it can be

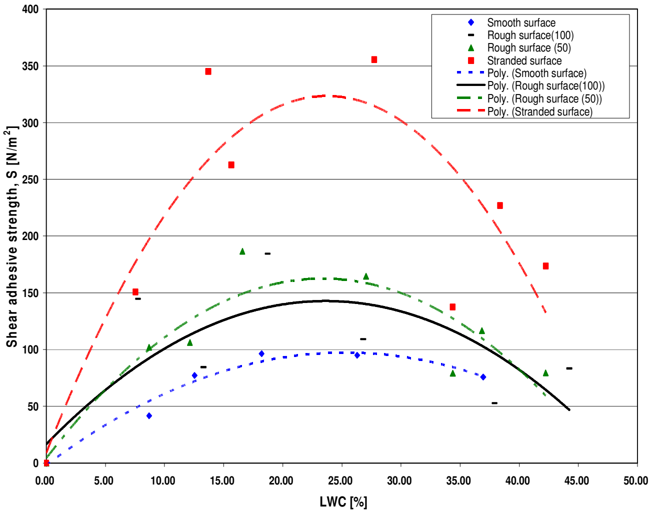

Fig. 5. Relation between LWC and shear adhesive strength for wet snow

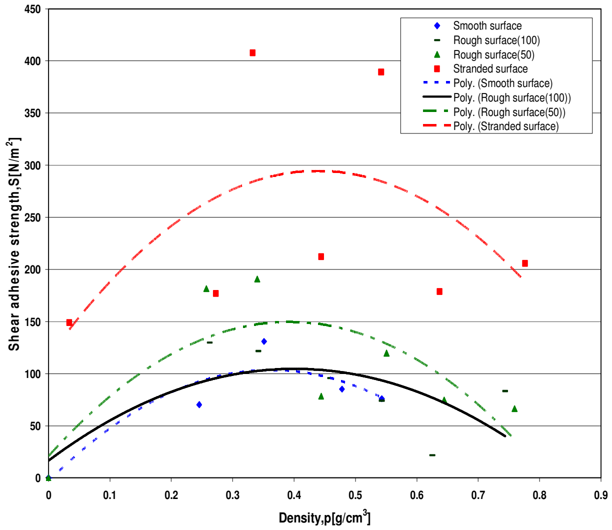

Fig. 6. Relation between density and shear adhesive strength for wet snow

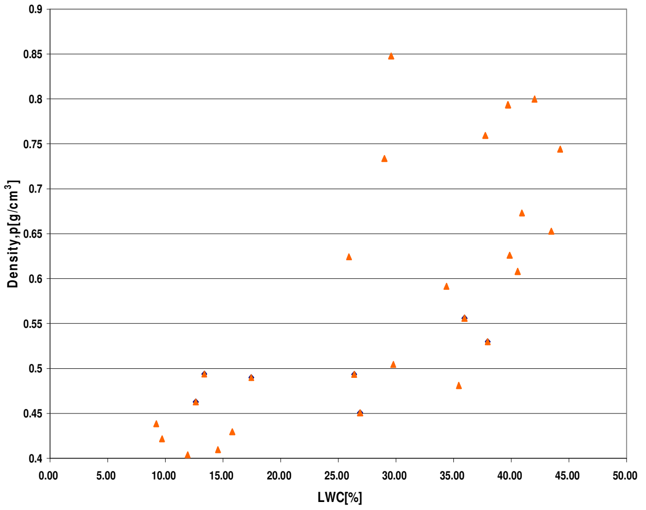

Fig. 7. Relation between LWC and density of wet snow samples

viewed that the shear adhesive strength of snow is greater on stranded beams than on rough surfaces prepared with sandpaper No. 100 or 50, which are very close to each other.

B. Tensile Adhesion Tests

1) Test Results

Similarly to the presentation of shear adhesion tests, average values in each 5% interval for LWC or 100 kg/m^3 for density are plotted in the graphs. Figure 8 describes the relation between tensile adhesive strength and LWC. It can be noticed that tensile adhesive strength is high comparing with shear strength; it is about 10 times greater. The strength increases with LWC until a certain range, and it decreases after reaching a maximum. The maximum strength can be found between 22 and 32% of LWC. This tendency may be explained by the smaller contact area between snow particles and cable surface for lower values of LWC. When the LWC increases, the contact area also increases, and correspondingly, the adhesive force and strength will be greater. Furthermore, the snow grains near the interface are compressed by the initial compression, and when the snow grains are locally densified, the radius of curvature of the concave water becomes smaller, and the strength increases with decreasing curvature. However, when snow contains large amount of water, most of air voids are saturated, which decreases the strength [13].

Figure 8 also shows that tensile strength for smooth surfaces is greater by a factor of about 2.5 than for stranded surfaces, and it is slightly greater than for rough surfaces prepared with sandpaper no. 50. This result might be obtained due to the fact that the snow particles were compressed greatly on the stranded plates, and some snow stayed in the grooves even after the detachment as shown in Fig. 9. Thus, the real contact area between the plate and the detached snow might be reduced significantly, but the surface of the snow sample was considered in the calculations. Therefore, the tensile stress is underestimated in Fig. 8. However, it is still lower than the stress on the other surfaces, because the tensile force was measured smaller.

Regarding Fig. 10, the tensile strength increases until the density range from 0.5 to 0.8 g/cm^3, then it begins to

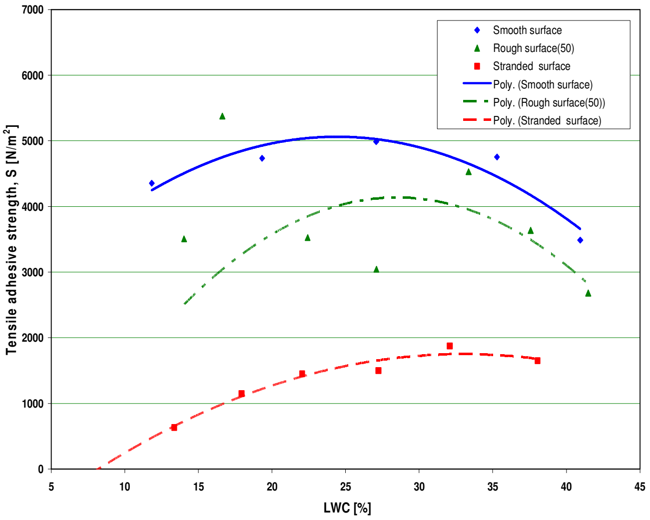

Fig. 8. Relation between LWC and tensile strength for wet snow

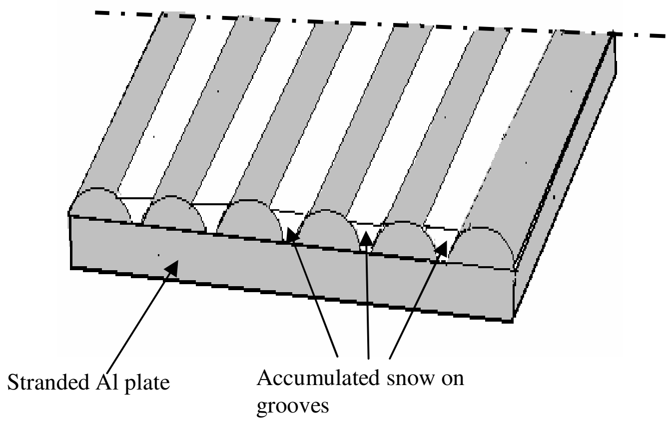

Fig. 9. Snow attachment on the stranded cable

decrease similarly to the trend, as explained in the last sections, that at moderate values of LWC or density the maximum values of adhesion can be found. Also it can be noticed in the graph that higher tensile strength was measured on smooth surfaces than on stranded surfaces.

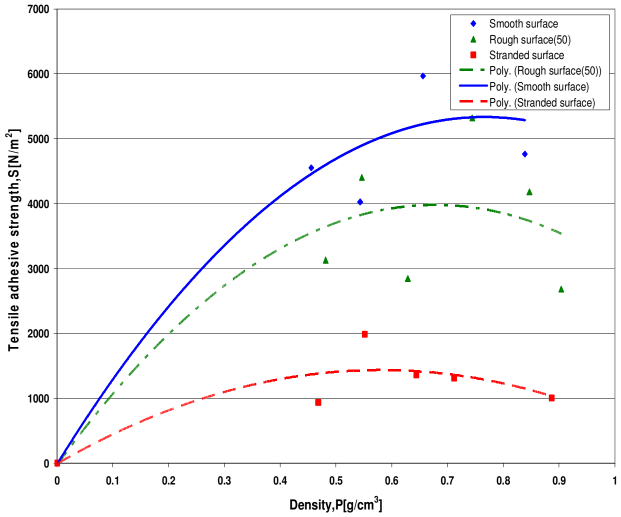

Fig. 10. Relation between density and tensile adhesive strength for wet snow

Figure 11 explains the relation between LWC and density of wet snow. It can be observed that the density of snow increases with its LWC. The values of LWC which give the maximum adhesive forces, which were found between 22% and 32%, correspond to the density values between 0.5 to 0.8 g/cm^3 for tensile tests.

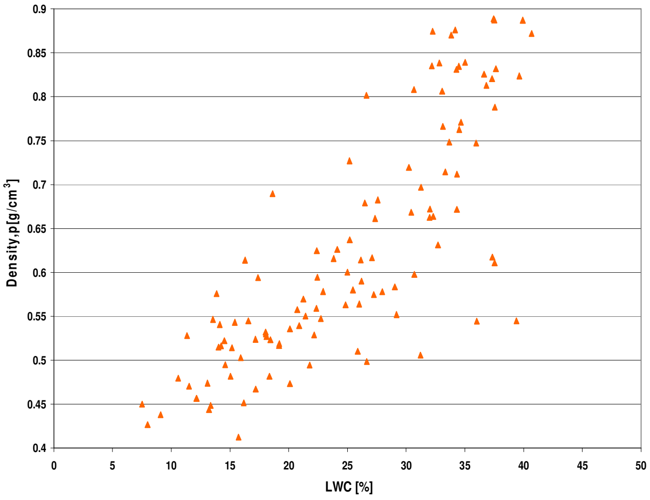

Fig. 11. Relation between LWC and density at tensile for wet snow

2 *Comparison to the Former Results*

Results are in agreement with those of other investigators [13] in the sense that the tensile strength for both former and present results increases with LWC until a maximum value, and then decreases with higher values of LWC (see Fig. 12). However, the maximum values of tensile strength have been obtained for different LWC. In former results, the maximum strength was reached in a range from 12 to 16% of LWC, but it lies in the LWC range of 22 to 27% for the present results. One reason of this discrepancy may be that the test procedures were not identical in the two studies. The maximum compression force in the current procedure was chosen to be 80 N, which is greater than the force in the procedure of [13]. This is necessary to obtain a tensile force that is great enough to make the MTS machine sensitive to it. However, the sample size was also greater so that the compressive stresses in the two studies were approximately the same. Additionally, the authors of [13] started the pulling up of the plate after the compression force decreased to its quarter, whereas in the present study the application of tension began at a constant time after the compression was stopped. The time when the compressive load was reduced to its quarter was quite changeable; this is why choosing a constant time was found to be more pertinent considering the loading conditions.

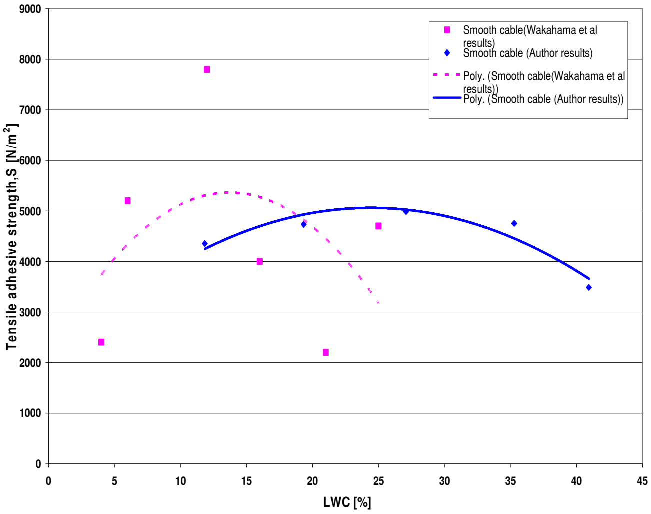

Fig. 12. Comparison between former and recent results; relation between LWC and tensile adhesive strength for smooth surface

V. CONCLUSIONS AND RECOMMENDATIONS

Shear and tensile adhesion of snow to cable surfaces was studied experimentally. The adhesive strength was determined as a function of snow characteristics, particularly liquid water content and density, and of roughness of cable surface. The following conclusions can be drawn from the obtained results:

- The greater the roughness, the greater the shear adhesion, however, the opposite is observed for tensile adhesion.
- The shear force or the shear strength increases as the LWC increases, reaching its maximum at 20 to 25% of LWC, followed by decreasing at higher values of LWC.
- The shear strength also increases as density increases, up to density values ranging between 0.4 to 0.5 g/cm^3; after that the shear strength decreases at higher values of density.

- Tensile adhesive strength is about 10 times greater comparing with shear strength.
- The tensile force or strength increases with LWC until a maximum occurring between 22% and 32%, and then decreases. The tensile force or strength on a smooth surface is about 1.5 times greater than that on a stranded surface, and close to that on a rough surface.
- The tensile strength also increases as density increases, up to density values ranging between 0.5 to 0.8 gm/cm^3, after that the tensile strength decreases at higher values of density.

It can be recommended for future work to study the effects of ambient parameters, such as air temperature, wind speed and precipitation rate, on tensile and shear strength of snow. These adhesion studies can be used to construct a material model for snow, which is essential for the simulation of dynamic effects on a cable covered by snow.

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