Studies on Tensile Strength of Wet Snow

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With a view to snow accretion on electric wires, railway trains, parabolic antennas and other structures, experimental studies were conducted on the tensile adhesive strength of wet snow onto various kinds of both hydrophilic and hydrophobic materials as a function of free water content of a snow sample ranging from 4 to 30% and compressive stress ranging from 1.5 to $18KN/m^2$ when the snow sample was initially brought to contact with a material. For a small initial stress the adhesive strength of snow was small, though varying with different material used, and remained constant for each of them regardless of the free water content of snow. Meanwhile, for a larger initial stress, it was large and increase in free water content; namely, for the initial stress more than $15KN/m^2$, it had the maximum when the free water content was 12-16%, whereas it was unexpectedly large for hydrophobic materials, being of the same order of magnitude as the one for hydrophilic materials. For a heavily wet snow, a linear relationship was obtained between adhesive strength and initial stress. The adhesive strength of snow onto rubber materials was always small regardless of initial stress and free water content. Direct microscopic observations were made of behaviours of water in contact with a glass plate as it was found in a capillary state, enveloping or inundating wet snow particles.

Introduction

Snow is very adhesive material. In particular, wet snow containing free water is adherent to any other materials. Falling snow flakes, for instance, easily accrete on electric wires, telephone lines, parabolic antennas, trains, automobiles and other structures, which causes much trouble and impediment in power transmission, communication, transportation, and so on. Cables are torn off and transmission towers crashed down at times by a heavy snow accretion almost every year when a strong cyclone is passing by the northern Japan (1).

It may be assumed for wet snow that a negative pressure is induced in water existing at an interface between a snow sample and a contacting material and that it makes the snow adhere it. The pressure, p, is given by the formula $p=-(\sigma/r)$, where σ is the surface tension of water and r is the radius of curvature of a concave water surface at the interface. The value of r may depend on factors which include free water content, grain size and density of snow, contact angle between water and a material. The adhesive force between wet snow and various kinds of materials is, therefore, very important in the study of practical problems.

Although extensive studies have dealt with ice adhesion (2, 3), only a limited number of studies have been conducted on adhesion of snow (4, 5). This paper presents the results of an experimental study on the tensile adhesive strength of wet snow onto various kinds of hydrophilic and hydrophobic materials including aluminum, glass, cellulose acetate, vinyl, teflon, polyethylen, silicone-rubber, ethylene-propylene rubber and butyl-rubber, which were brought into contact with snow samples with different free water contents and at different initially given compressive stress.

Experimental apparatus

The tensile adhesive strength, S, is defined as a value of F/A, where F is the tensile adhesive force and A is the apparent contact area between two contacting materials. In case of wet snow in contact with another material, it is not very easy to measure accurately the value of A. If an adhesive force is measured between a flat surface of wet snow and the other material, the apparent contact area is apt to be over-estimated resulting in the underestimation of the adhesive strength. A semi-spherically shaped snow sample 50mm in diameter was used in the present experiment, because it was confirmed after careful calibrations that the apparent contact area could be obtained very accurately.

A thin plate 3mm in thickness was sliced from each material prepared. A semi-spherically shaped snow sample was slowly compressed from on the top of it by the plate by moving it downward at a constant speed of 1mm/min by a motor through reduction gears, under which a strain-gauge type force measuring device was placed as shown in Fig.1. The compressive force increased with time as illustrated in Fig.2, and the motor was stopped at the moment when the force reached, for instance, 1.6N. It was followed by relaxation of stress. When the force reduced to a quarter of the initially given compressive force, the pulling up of the plate was started by the motor at the same speed as in case of initial compression.

The sign of the force soon changed from compressive to tensile, and the tensile force linearly increased with time until the plate and the wet snow sample were separated from each other as shown in Fig.2.

Figure 1. Experimental apparatus for measuring tensile adhesive strength of wet snow. U: strain-gauge type force-measuring device. P: a plate in contact with a semi-spherical snow sample.

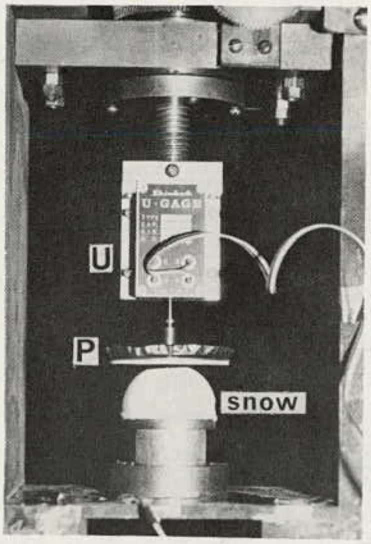
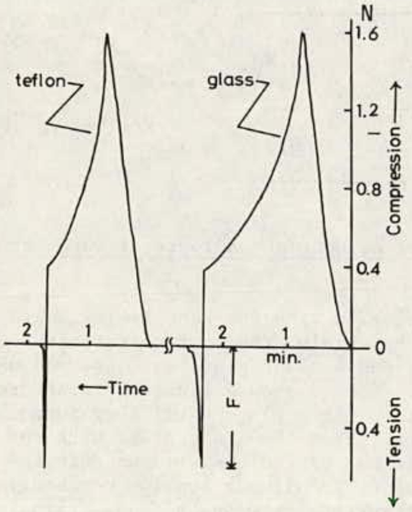


Figure 2. Examples of adhesive force-time curves.



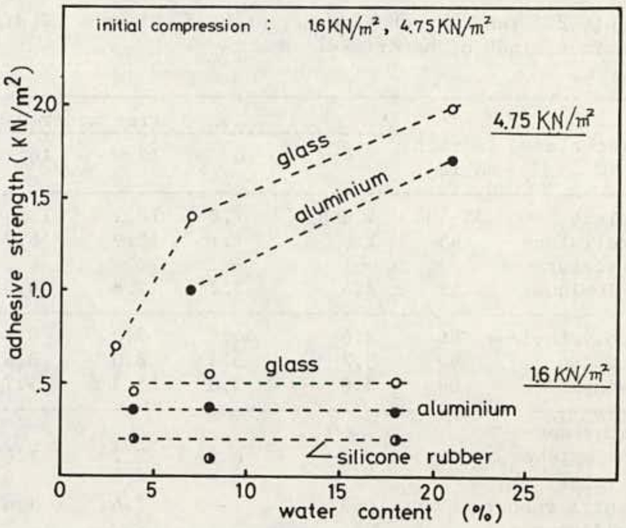
The apparent contact area was obtained both by measuring directly the diameter of the circular shaped contact plane on top of the snow sample and by using the time duration of initial compression, the compression speed and the geometry of the semi-spherical snow sample. The values obtained by these two methods agreed very well.

Experimental results

The adhesive strength was obtained by dividing the adhesive force by the apparent contact area. The adhesive strength of wet snow onto various materials thus obtained were tabulated in Tables 1 and 2 for different free water contents that ranged from 4 to 30% and for different initial compressive stress as given at the contacting surface. The contact angle between water and a plate made of each material was measured as listed in the second column of Table 2.

For a small initial contact stress such as $1.6\mathrm{KN/m^2}$, the adhesive strength was found smaller than $0.5\mathrm{KN/m^2}$, and it remained constant for each material regardless of free water content of snow as seen in both Fig.3 and Table 1. For a larger initial stress such as $4.75\mathrm{KN/m^2}$, the larger adhesive strength was observed, which increased with an increase in free water content of snow as shown in Fig.3.

Figure 3. Adhesive strength vs. free water content of snow for different initial compressive stresses.



When the initial contact stress of about $15\mathrm{KN/m^2}$ was applied to a snow sample, the adhesive strength became larger for each material with an increase in free water content of snow, whereupon it was found maximum when the free water content was 12-16%, as seen in Table 2 and Fig.4.

Figure 4. Adhesive strength vs. free water content of snow for a large initial compressive stress of $15\mathrm{KN/m^2}$.

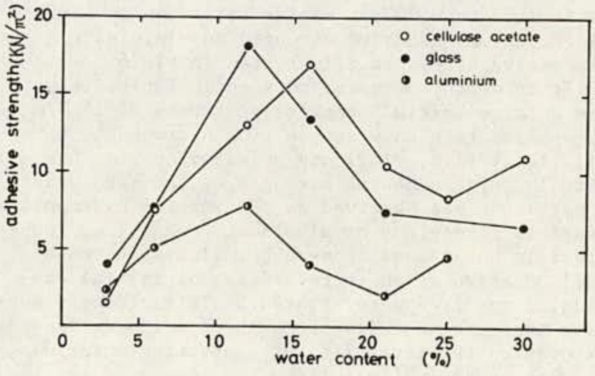


Table 1. Tensile adhesive strength of wet snow onto various kinds of materials for different free water contents and for two initial compressive stresses.

Initially applied compressive stress	$1.6 KN/m^2$			$4.75 KN/m^2$	
Free water content of snow (%)	4	8	20	7	20
glass	$0.4-0.5 KN/m^2$	0.5	0.4-0.5	1.5	0.20
cellulose acetate	0.4	0.5	0.5	1.0	0.9
aluminum	0.3-0.4	0.3-0.4	0.3-0.4	1.0	0.17
polyethylene	0.2	0.2	0.2	0.7	0.7
teflon	0.2	0.2	0.3	---	---
vinyl	0.1-0.2	0.1-0.2	0.2	---	---
butyl rubber	0.2	0.1	0.2	0.2-0.3	0.2-0.3
silicone rubber	0	0.1-0.2	0.1-0.2	0.2	0.2-0.3

Table 2. Tensile adhesive strength of wet snow of different free water contents to various kinds of materials.

Material	Contact angle	Free water content (%)						
		4	6	12	16	21	25	30
glass	35-40°	$4.0 KN/m^2$	7.8	18.2	13.4	7.4	---	6.5
cellulose acetate	65	1.6	7.7	12.9	16.9	10.4	8.4	11.4
aluminum	59	2.4	5.2	7.8	4.0	2.2	4.7	---
polyethylene	86	3.6	4.4	8.0	8.3	---	6.9	5.5
teflon	90	5.2	3.4	8.0	8.6	---	---	10.
vinyl	89	2.0	3.0	13.3	5.7	---	4.8	---
ethylene-propylene rubber	78	0	0.9	2.2	1.6	1.0	---	0.3
butyl rubber	85	0.5	---	1.4	1.4	---	---	---
silicone rubber	90	0.5	0.4	---	0.5	---	0.2	0.3

Such large values as $15-18 KN/m^2$ observed at the free water content of 12-16% may be due to a smaller contact area of snow, because the adhesive force itself remained constant for each material when the free water content of snow was larger than 7-8% as illustrated in Fig.5. In fact, a smaller contact area was observed for the snow containing free water of 12-16% than that observed for the snow which contained free water of less or more than these percentages.

For a heavily wet snow containing free water of 20% or more than 20%, a linear relationship was obtained between adhesive strength and initially given compressive stress as illustrated in Fig.6.

It is worthy of note, as seen in Table 2, that when a large initial compressive stress of $15 KN/m^2$ was applied to a snow sample by a hydrophobic material like teflon, vinyl and polyethylene, an unexpectedly large adhesive strength of the same order of magnitude was observed as the one for hydrophilic materials like glass or aluminum. Meanwhile, rubber materials such as silicon-rubber always showed a small adhesive strength regardless of initial compression and free water content. This strongly suggests that the adhesive strength of wet snow depends not only on the wettabilty of contacting materials, but also on their flexibility.

Direct observation of behaviours of water at the Interface

In connection with the adhesive strength of snow onto other materials, the contact surface between snow grains and a glass plate was observed under a microscope. Sieved snow grains were scattered to be adhered onto a glass plate until they formed two or three layers. Then the glass plate with the snow grains on it was placed upside down onto the stage of a microscope to allow a continuous observation of the contact surface between the snow grains and the glass plate at the room temperature kept between 0° and +1°C. Snow grains began to melt, resulting in an increase in the amount of meltwater with time. At the beginning stage, each snow grain was enveloped by a small amount of water at its bottom as seen in Fig.7(a). The side view of such snow grains is schematically shown in Fig.9(a). With an increase of the amount of meltwater, an increasing number of snow grains were immersed in an assemblage of water as shown in Fig.7(b). and Fig.9(b). Finally, the whole snow grains formed a continuous water mass on the glass plate as shown in Fig.9(c).

To examine the behaviour of water existing at the interface at the time of its separation from one another, a method was designed using two combinations, i.e., a glass plate and a brass plate, and a teflon

Figure 5. Adhesive force vs. free water content of snow

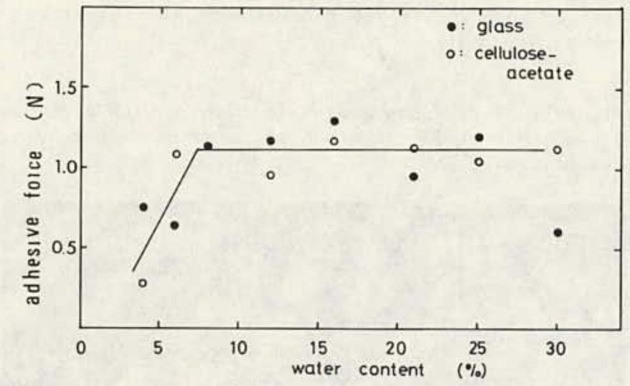


Figure 6. Relationship between adhesive strength and initial compressive stress for wet snow containing 20% of free water.

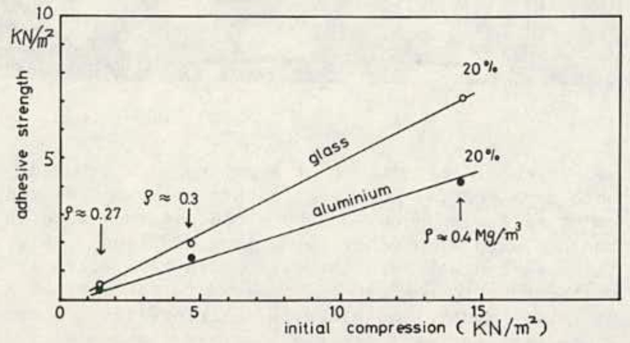


plate-a brass plate. Two photographs in Fig.8 show the shape of water at the interface immediately before a complete separation.

The distance between the surface of snow and the contacting plate at the moment of separation was estimated by using the time duration of tensile adhesion and the tension speed (1mm/min), and it was found that the separation distance was 30-35μm and 50-70μm for hydrophobic and hydrophilic materials, respectively. The difference in the separation distances is reflection of the difference in the contact angles between hydrophilic and hydrophobic materials as seen in Fig.8.

Discussion

It was observed under a microscope that a contact surface was wetted by water for each of snow samples containing different amounts of free water. This suggests that only the water existing at the interface plays the dominant role in adhesion of wet snow. If there is no water at the interface, i.e., in case of dry snow, only a very small adhesive force is to be expected. In fact, such a force was observed for dry snow when it was measured one minute after it was brought to contact with a glass plate at a temperature of -5°C.

Experimental results show that when a small initial stress such as $1.6 KN/m^2$ was applied to a snow sample, the very small adhesive strength S was observed for each material regardless of the free water content, w, of snow. This may be due to a "poor" contact between a snow sample and a test plate under such a small initial contact stress as $1.6 KN/m^2$.

Figure 7. Wet snow grains in contact with a glass plate. a: small amount of free water; b: larger amount of free water. Scale: 1mm.

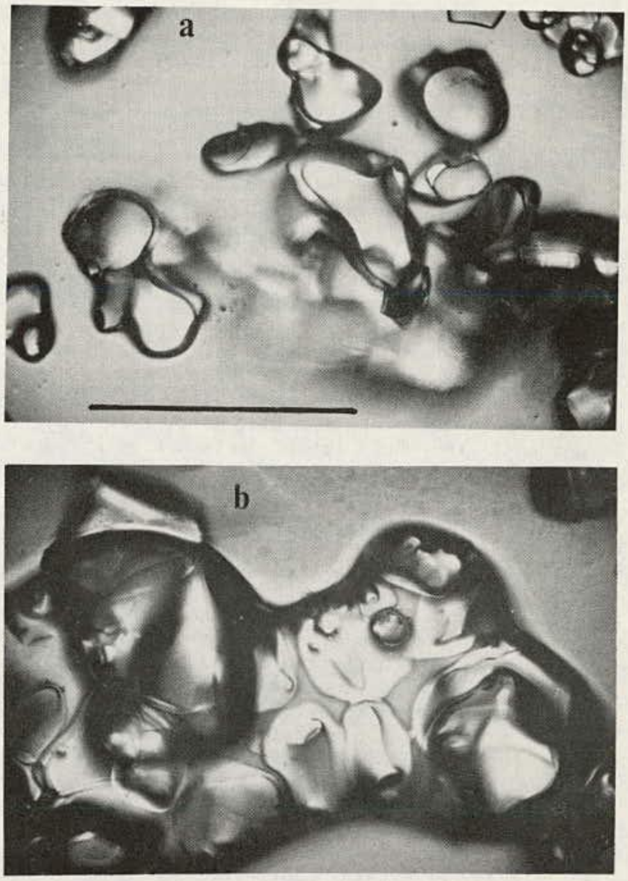
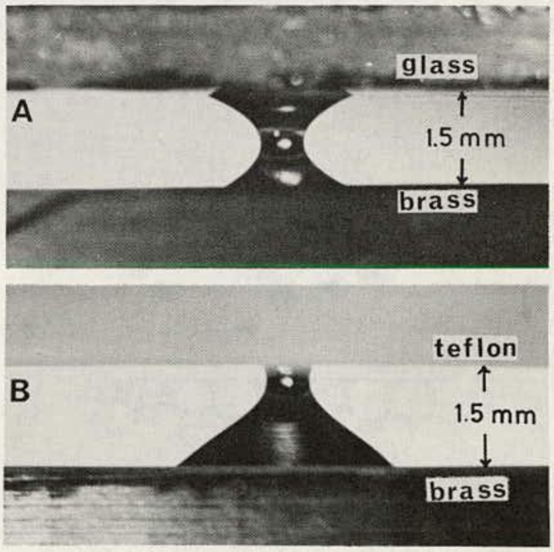


Figure 8. Simulated side view of water at the interface immediately before a complete separation. (A: a glass plate and a brass plate; B: a teflon plate and a brass plate)

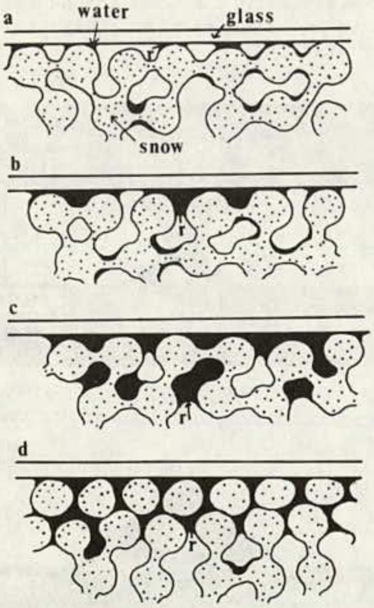


When the initial compressive stress such as more than $3\text{-}4 KN/m^2$ was applied to a snow sample, the adhesive strength S became dependent on the free water content w, and the maximum value of S was found when w was 12-16% as shown in Fig.4 and Table 2. These results can be explained as follows: As described before, the adhesive force F of wet snow may be dependent on the negative pressure $p=(-\sigma/r)$ induced in water existing at an interface between a wet snow sample and a contacting plate, and also the sum of the area B of water in contact with the plate; hence $F=B\cdot(\sigma/r)$ and the adhesive strength $S=(B/A)\cdot(\sigma/r)$, in which B and r vary with the interfacial snow density, free water content, grain size of snow, contact angle between a water droplet and the plate, and time duration after the contact. The grain size of snow, the contact angle and the time duration are the same for each experiment, and the interfacial snow density may depend on the initial compressive stress.

When a snow sample contains only a small amount of water less than 10% in free water content, the area B is so small that F, hence S, is small (Fig.9a). As the free water content w increases, B becomes larger until the whole interface is wetted by water when (B/A) reaches the maximum value of 1. In addition to this, it is probable that snow grains near the interface is locally compressed by the initial compression as schematically shown in Fig.9d. When the snow is locally densified, the radius of curvature r of the concave water surface at or near the interface becomes smaller because the distances between neighbouring snow grains become small as illustrated in Fig.9d. This state may be realized when a snow sample contains free water of 12-16% for which the maximum value of adhesive strength S was observed.

When a snow sample contains a larger amount of water such as 20-30%, most of air-voids among snow grains are saturated with water and r becomes larger as shown in Fig.9c, while the adhesive strength slightly decreases when the free water content becomes too large (Fig.4).

Figure 9. Schematic diagrams of water existing at or near the interface between snow and a glass plate. For different free water contents of snow (a, b and c). d; for the snow densified at the interface by an initial compression.



The shear adhesive strength of wet snow is of minor importance in a snow accretion problem compared to its tensile adhesive strength, because the former is generally much smaller than the latter; for example, the value of the latter onto electric wires was $0.19\mathrm{KN/m^2}$ when the free water content was greater than 20%, while the value of the former was only $0.02\mathrm{KN/m^2}$(1).

Figure 10. Dry snow grains in contact with a glass plate. Mirror-like contact plane surfaces are seen. Scale: 1mm.

It should be noted that even dry snow adhered onto any material at a temperature below the melting point of ice such as -5° and -10°C, if they were in contact with each other for a long duration of time. The real contact area increased with time after it was brought to contact and adhered to the surface of glass, metals and plastics. Mirror-like contact plane surfaces were clearly observed under a microscope as illustrated in Fig.10.

Acknowledgements

The present authors wish to express their sincere thanks to Dr.E. Akitaya and Y. Endo for their suggestions and useful discussions throughout the work. This study has been made possible by a support from the Ministry of Education of Japanese Government, which is gratefully acknowledged.

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