BY REINHARD MOOK

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Aircraft braking coefficient is affected by liquid water in frozen runway contamination.

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Lingering uncertainty associated with measured and estimated runway friction and aircraft braking coefficients can lead to landing distances or maximum landing weights that also are uncertain or inaccurate. "This has contributed to accidents and incidents where aircraft departed runways because the surface was more slippery than expected," according to the executive summary of a study released in 2011 by the Accident Investigation Board Norway (AIBN).[1]

In 30 investigated occurrences, the AIBN found that "aircraft braking coefficient (ABC) was not in accordance with the measured/estimated runway friction coefficients (FC)." In its study, the AIBN identified a number of common factors that have reduced safety margins, and factors that explain the differences between ABC and FC. "These factors are related to meteorological conditions and friction measurement uncertainty, runway treatment, operational aspects and regulatory conditions," the AIBN study said.

Among the factors is the wetness of snow, or the volume percentage of liquid water in frozen runway contamination. The author carried out a study of wetness in frozen contamination at Svalbard Airport, Spitsbergen, Norway, from 2009 through 2012 under the auspices of AIBN in order to better understand aircraft winter operations following the board's comprehensive report.

Results of the author's study show that wetness in falling snow, or recently fallen snow, decreases with surface air temperature, except for specific cases related to temperature inversions. Recently fallen snow that is not exposed to further precipitation or thawing partially dries up in the course of hours, thus improving braking conditions. In such situations, estimated aircraft braking performance based on the ABC value closely correlates with contemporary observed wetness in samples of frozen contamination.

Essential Indicators

As shown by the 2011 AIBN study, measurements of braking action by conventional devices are difficult to rely on, particularly in the critical temperature range near freezing or when there is wet, compacted frozen contamination. The present study draws attention to wetness in frozen contamination. Though interrelated, wetness and surface temperature, together with the three-kelvin-spread-rule (which indicates that a difference between dew point and METAR, the current aviation meteorological report, air temperature [2 m or 6.6 ft above the runway surface] of 3 three kelvins or less indicates that the humidity is 80 percent or more; a kelvin [K] is 3 degrees C or 5.4 degrees F), might prove to be essential indicators for braking action to be expected.[1,2]

Recent snow may contain a large proportion of liquid water. When such snow is compacted, its surface becomes coated with a film of liquid water, hence the ability to transfer shear force (that is, braking) at the microscopic level between tire and runway surface materials is reduced. Similar conditions happen when compacted snow or ice is thawing at its upper surface. Compressed snow transformed to ice disintegrates gradually when the melting point temperature is approached as the surfaces of frozen particles are enveloped by liquid water. The static stability of the ice decreases and reinforces the lubricating effect of free liquid water in contact with a decelerating tire.

Additional liquid water is generated in the footprint of tires due to the flash melting of ice caused by tire dynamics. Experience shows that the total outcome of braking as described by the ABC is partially related to the portion of liquid water in the frozen contamination. That portion might be relevant for runway management.

Moisture Measurement Challenges

To determine wetness in snow or ice, the difference in permittivity (the dielectric constant[3]) of frozen versus liquid water often is used by micrometeorologists in this area and has turned out to be useful in snow and ice research. The Denoth Dielectric Moisture Meter[4] is based on that difference and allows the proportion of liquid water to be determined when the density of the snow is known. A flat capacitive sensor was used in the author's research, with one side

Number of Cases for Classes of Wetness and Air Temperature at 2 m

Wetness Volume (%)	Air Temperature (°C) ≤ –15	–14 to –10	–09 to –05	–04 to 00	≥ 00	Total
≤ 4	6	7	1	—	—	**14**
5–9	1	2	2	—	—	**5**
10–14	2	5	6	5	—	**18**
15–19	4	3	11	14	6	**38**
20–24	—	—	5	6	11	**22**
≥ 25	—	—	—	2	2	**4**
Total	**13**	**17**	**25**	**27**	**19**	**101**

Note: Volume percent in recent snow.

Source: Reinhard Mook

Table 1

placed atop the frozen contamination and the other side left exposed to the air. The effective area covered by the sensor was about 160 cm^2 (25 in^2), and the operating frequency was 20 MHz. The sensitivity decreases strongly with distance inside the probe. This tool measures a layer of 1.0 cm (0.39 in) of compacted snow or ice. Ideally, there should be no caverns of air between the sensor and the frozen material.

The permittivity of a frozen layer can be calculated as a function of the voltage read when the sensor is placed upon the frozen contamination; the device works by comparing this to the voltage when the sensor is exposed to air, as the point of reference.To calculate liquid water content, the density of snow or ice is needed.

In field work at a runway, exposed to freezing temperatures, wind and often poor illumination, some uncontrolled errors in the measurements cannot be avoided. Compressed snow or ice rarely presents a smooth surface to make good contact with the sensor. In addition, grains of sand applied to a runway cannot be eliminated from the area to be measured, much less removed when enclosed in the frozen material. Sand affects the readings of wetness as well as the measurement of density. The depth of the contaminating layer is not constant and may include different horizons. Therefore the dielectric reading may be influenced by the permittivity of asphalt or concrete.

The challenge of attaining close contact between sensor and contaminating material was met by scraping together superficial snow or bars (studs) of snow or ice, and filling a freezing box to a depth of 6 cm (2.36 in). Thus the measurements of wetness were done at that 6-cm deep probe. The density was determined from the weight of the known volume, avoiding caverns of air. The readings were obtained in an area sheltered from wind.

Sample Readings

There is a relationship between air temperatures observed 2 m above ground (per the METAR) and wetness of snow. Compacted snow not older than one hour after precipitation, or cases with snowfall continuing at the time of wetness measurement, but after compression by traffic, were considered. Cases of blowing snow together with precipitation were excluded, as older, dried up snow might influence the results. The sample of 101 readings was the outcome of occasional observations, without equal probability for any combination of temperature and wetness.

Table 1 shows low temperatures — less than or equal to 9 degrees C (48 degrees F) — and the dichotomy in wetness observed. There are both cases of low wetness (less than or equal to 4 volume percent), as one would expect, and rather large figures of wetness (10 to 19 volume percent). When temperatures aloft at the 850 hPa (25.1 in Hg) pressure level were checked, it turned out that comparatively wet snow in low ground level temperatures was due to temperature inversions and advection or transfer of warm air above. Other cases were due to snow showers in an Arctic maritime air mass with a near moist adiabatic gradient of air temperature. Therefore, as a rule, measuring wetness of snow, which is not yet accepted as a standard practice in runway management, should not be done from ground air temperatures only. Temperatures aloft should be considered as well.

Otherwise, wetness increases with ground level air temperature. Figures for temperatures greater than or equal to 0 degrees C (32 degrees F) cover all the cases of very wet snow or snow and rain accumulating frozen material in airport ground operations. Frequently, rain only is observed when the air temperature exceeds about 3 degrees C (37 degrees F). The maximum wetness observed from 26 to 27 volume percent is limited by the ability of the frozen material to retain liquid water.

Wetness in Snow Over Time

When snowfall ends, sweeping may result in compacted snow, probably on top of older contamination. Over time, the snow will dry up due to internal freezing and crystal growth, ice bonding to material at the bottom and evaporation. All these processes depend on gradients of internal and external temperatures, together with ventilation (wind). Frequently, when precipitation has stopped and the cloud cover has dissipated, the temperature falls and the dew point to frost point spread increases. Every case is different, but the drying up in the course of time may be of interest for defined conditions, as braking action might improve.

The 17 cases considered had, at the end of snowfall, wetness between 24 and 10 volume percent. That starting wetness was assumed as 100 percent in all cases, as it turned out that drying up could be described in terms of the percent of the actual starting wetness. The development in weather terms meant scattered clouds to clear sky after precipitation and decreasing snow surface temperature as measured by an infrared sensor.

Table 2 shows as a mean value that wetness of snow was reduced by 75 percent after eight hours. In the cases observed, mean surface temperature had dropped from minus 4 degrees C (25 degrees F) to minus 11 degrees C (12 degrees F), and the spread of METAR air temperature and frost point temperature (defined for ice instead of dew point defined for liquid water) had increased to 5 K.

The general experience of pilots that friction may be poor on recent snow, but that it improves over the course of hours, is consistent with the observed drying up and decrease of surface temperature. It may be concluded that liquid water in compacted snow is relevant for braking conditions. There are interrelations among the mechanics of ice crystals, liquid water enclosed in ice aggregates, temperature and the frozen material's ability to transfer shear forces.

Wetness and Braking Coefficient

The relationship between ABC and wetness is essential for runway management involving frozen contaminants. Figures on deceleration experienced by aircraft were not available for the author's study. Therefore, such figures had to be estimated, as described previously by the author.[5] The method can easily be criticized for some subjectivity, so the given ABC should be treated as an indicator only.

The ABC derived represents cases when the mean headwind component was less than 8 kt. Otherwise, different kinds and structures of frozen contamination are represented in the sample of 62 cases. In Table 3, the independent variable

Decrease in Percent of Wetness From the End of Snowfall Through Time

Time from start (hours)	0	2	4	6	8
Percent of wetness at start (%)	100	87	51	33	24
Mean surface snow temperature (°C)	–4	–7	–8	–10	–11
Mean frostpoint spread (K)	1	3	5	6	5

Note: Actually observed liquid water volume percent put to 100. Sample cases = 17.

Source: Reinhard Mook

Table 2

Wetness in Surface Snow Related to Estimated ABC

Wetness Volume (%)	ABC	Surface Temperature (°C)	Air Temperature (°C)	Spread (K)	Number
≥ 25	0.05	0	3	1	1
24–20	0.04	0	2	2	3
19–15	0.06	–1	–1	3	6
14–10	0.07	–4	–3	3	13
9–5	0.11	–8	–6	5	24
≤ 4	0.14	–10	–9	6	15

ABC = aircraft braking coefficient

Note: Total number of cases = 62.

Source: Reinhard Mook

Table 3

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is wetness in terms of liquid water volume percent. Mean surface temperature (measured by infrared sensor) and mean air temperature (as reported in the METAR), together with spread related to dew point temperature, are given. The ABC is expressed for Boeing 737-800 aircraft. As a rule, the contaminated runway was sanded, from prior or recent application, or both. Frequently, warm sand was applied.

Though observations were made preferably when wetness was large, there was a bias toward more observations when wetness actually was small. Thawing or very wet precipitation are not frequent occasions, as compared to all the days with "dry" conditions. Flights are canceled or diverted when expected braking action is reported as poor.

Table 3 shows increasing ABC with decreasing wetness, notably when it gets less than 10 volume percent. These rather dry conditions in the sample occur together with decreasing temperatures and increasing spread. As shown in a previous study, ABC usually improves with decreasing surface temperature and increasing spread (except for polishing effects). Wetness and surface temperature turn out to be good indicators for ABC due to meteorological feedback interdependencies.

It should be noted that case studies could offer more details worth considering, although they represent unique situations. But each case study, by eliminating distracting details, might reveal insights not seen in statistical analysis alone.

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Notes

1. AIBN (2011) *Winter Operations, Friction Measurements and Conditions for Friction Predictions.* Accident Investigation Board of Norway (Statens Havarikommisjon for Transport), Lillestrøm, Norway.
2. Mook, R. "Valuable Intelligence." *AeroSafety World* Volume 6 (November 2011):16–19.
3. The velocity of the propagation of electromagnetic waves relative to the velocity in a vacuum, depends on that constant. It is specific for any substance, except ferromagnetic material not propagating electromagnetic waves. The constant respective velocity for ice is significantly different from liquid water, a property applied. Velocity and refraction are linked together, as is well known from the spectral colors of sunlight in ice crystals due to refraction.
4. Denoth, A. (1994) "An electronic device for long-term snow wetness recording." *Annals of Glaciology*, 19, 104–106.
5. Mook, R. "Treacherous Thawing." *AeroSafety World* Volume 3 (October 2008):14–19.