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Angle of repose of granulated ice: effect of wood ash

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Abstract

New experiments have revealed that the addition of a small amount of wood ash doubles the angle of repose of granulated ice at −10°C, but has little effect at −30°C. It is hypothesized that this behavior may be explained in terms of the freezing of water that is formed at the higher temperature through the reaction of salt within the ash.

1. Introduction

The angle of repose (AOR) is a fundamental characteristic of granular materials. In cold environments, this characteristic plays a role in avalanche dynamics and infrastructure stability. In snow, for instance, it is governed by an interplay of factors, including temperature and particle shape and size (Willibald and others, 2020; Eidevåg and others, 2022). Foreign particles introduced through volcanic eruptions, industrial activities and natural wildfires may also play a role (Conway and others, 1996).

In this paper we describe the effect of wood ash on the ARO of granulated ice. The study was motivated by the fact, known by wood-burning inhabitants of cold regions, that ashes, when sprinkled on icy surfaces, offer an effective method of improving both foot and vehicle traction. The AOR may be viewed as a measure of friction and hence of traction. As will become apparent, a very small amount of ash has a large effect on AOR. To our knowledge, this is the first report to quantify the effect of wood ash on this characteristic.

2. Experimental procedure

The ice used in this study was produced through the solidification of fresh water (i.e., Hanover tap water) and then granulated by breaking with a hammer and refining in a blender. The particles varied in diameter from 1 to 16 mm. They were separated into two groups, one whose particles ranged in size from 1 to 8 mm; the other, 8–16 mm.

The ash was produced through the burning of oak in a wood-burning stove. It was mixed with the granulated ice, up to the amount of 10% by volume, as follows. The ice was placed in a 20-l container (at −10°C) and the appropriate amount of ash was placed on top. Subsequently, the two components were mixed by hand, first by stirring using a wooden paddle and then by shaking the container for few minutes. Mixing was judged to be complete when the mixture appeared to the naked eye to be uniform.

To create a pile, either ice itself or an ice-ash mixture of a given ash fraction was poured into a plastic funnel (with dimensions of 31 mm at its narrower opening and a volumetric capacity of 1 l) that was affixed to an apparatus to ensure stability during the experiment. Figure 1 shows the setup. Initially the open end of the funnel was sealed. Subsequently, the seal was removed and the contents of the funnel were allowed to fall from a height of 12 cm (measured from the bottom of the funnel) onto a polymethylmethacrylate plate that had been cleaned by washing in soap and water prior to the experiment. Unlike the experiments of Willibald and others (2020) in which a retaining edge was used to prevent snow from spilling out too far as it fell upon the base, no constraint was used in the present experiments.

To obtain the AOR, the height, h, and the diameter, d, of the pile were measured. The height was measured using a calibrated ruler. The diameter was obtained from the average of three to four measurements taken around the periphery, using calipers. The AOR was then computed from the relationship $AOR = \arctan(2h/d)$. As apparent from Figure 2, the top of the pile was generally rather flat, especially for the more coarsely grained mixtures and so in those cases the AOR computed from the measured dimensions is probably somewhat lower than the actual angle. The error is estimated to be about 3 to 6 degrees.

The experiments were performed in a cold room. In one series the room was set at −10°C; in the other, at −30°C. The ice-ash mixture was allowed to reach thermal equilibrium before it was poured into the funnel. In the interest of reproducibility, each experiment was performed twice. In total, 40 measurements were made.

3. Results

Figure 2 shows the results. Data reported in this manuscript are available upon request. Most striking is the large effect of a small amount of ash on the AOR at −10°C. The

Figure 1. Image depicting the experimental setup and showing a pile formed from a mixture of 8–16 mm particles of ice +0.1 volume percent wood ash.

addition of 0.1 vol. percent essentially doubles the angle, from ∼12 to 28°. The addition of 0.2% increases the angle further, to ∼ 33°. Greater amounts have a progressively lesser effect, and the AOR tends to reach a limit of 35 to 40 ° upon the addition of 1.0 to 10% ash. Up to that limit, the AOR may be described by the relationship $AOR = AOR_o + \alpha\phi^n$ where AOR_o $\sim 12^o$, ϕ denotes the volume fraction of ash and (as found through separate analysis) $\alpha \sim 50^\circ$ and $n \sim 0.15$. Striking, too, is the diminished effect of ash at −30°C where over the range explored the AOR increases by less than 50%. Noteworthy as well is the lower AOR of ash-free ice at the lower temperature: 7 ± 1° at −30°C vs 12 ± 2 at –10°C. On particle size, a significant effect is not evident in the data, owing perhaps to the blend of sizes within our mixtures.

4. Discussion

This behavior may be explained as follows: The AOR may be viewed as a measure of the coefficient of friction which, in turn, is affected by several factors. The one most at play in the current experiments, we suggest, is inter-particle cohesion, although ash-induced abrasion and related changes in roughness probably play a role as well. Cohesion develops through the transformation to solid of a liquid-like-layer (LLL) that exists on the surface of ice at elevated temperatures (Faraday, 1860; Dash and others, 1995; Petrenko and Whitworth, 1999; Murdza and others, 2022), augmented at the higher temperature (−10°C = 0.96 homologous temperature) by the freezing of water that forms through the reaction of ice with salt, particularly calcium carbonite that is a large part of the chemical composition of wood ash (Etiégni and Campbell, 1991; Smołka-Danielowska and Jabłońska, 2022). The greater the ash content of the ice-ash mixture, the greater is the augmentation and so the greater is the fraction of the inter-particle interface that is wetted by the salt-induced water and then frozen to create cohesion. At the lower temperature (−30°C = 0.89 homologous temperature), the ice-salt reaction is either suppressed or nonexistent and the LLL is thinner (Dash and others, 1995; Petrenko and Whitworth, 1999), thereby either reducing or eliminating the liquid-to-solid transformation and leaving only the abrasive action of ash on ice.

That the ash in our experiments interacted with the ice as envisaged is supported by two additional observations. When sprinkled onto the surface of a plate of ice at −10°C, the ash stuck when the plate was turned over. At −30°C, it fell off.

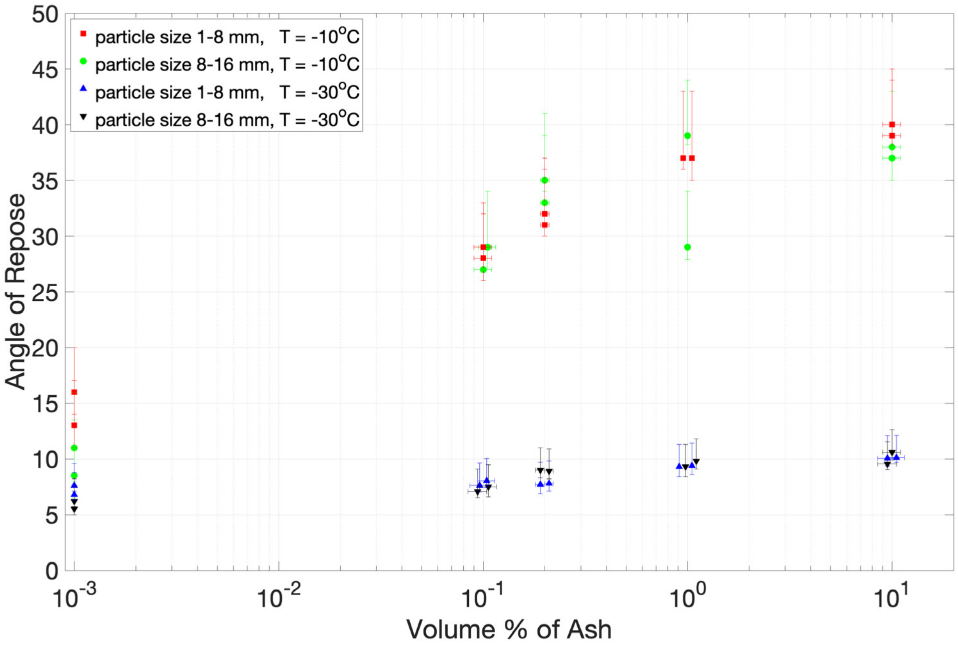

Figure 2. Angle of repose of granulated fresh water ice vs volume percent of wood ash.

Why does so little ash have such a large effect on AOR at −10°C? It is not necessary that the entire surface of an ice particle of diameter λ be decorated with ash of diameter δ. If that were the case, then the volume fraction needed, $\phi_{\max}$, would be rather high; i.e., $\phi_{\max} = 6\,\delta/\lambda \sim 6 \times 0.15$ mm/8 mm ~ 0.1 or ∼10% by volume for particles of wood ash whose average size is typically ∼0.15 mm (Etiégni and Campbell, 1991) and for ice of an average diameter of 8 mm. The fact that a much smaller volume fraction of ∼0.1% (Fig. 2) is needed to impart a large effect probably means that the water that forms wets a significant fraction of the inter-particle surface of the ice, leading to a relatively thin cohesive bond upon freezing, of the order of 0.1 δ/10 or 1 to 2 micrometers. The tendency of the AOR to saturate after only a small addition of ash suggests that once wetting is complete, little additional cohesion is imparted through the freezing of more inter-particle water.

In noting a relationship between AOR and friction, we caution that the coefficient of friction is not given simply by the tangent of the AOR. Friction of ice on ice is a complex process, where the coefficients of static and of kinetic (dynamic) friction exhibit different character (Schulson and Fortt, 2012, 2013) and are sensitive, among other factors, to time under load (static) and to sliding velocity (kinetic). A single measure from *tanAOR* does not capture this complexity.

Finally, given that snow and ice are closely related, how do their AOR's compare? From measurements by Eidevåg and others (2022), clean snow exhibits a steeper slope. Its AOR is between 25° (for crystals ∼200 micrometers in diameter) and 40° (for ∼100 micrometer crystals) compared with ∼12° for ice at the same temperature (−10°C) and drop height (0.1 m). The much finer particle size of snow than of the clean ice in our experiments and hence of the snow's greater surface to volume ratio --greater by a factor of 50 or more-- may be one reason for this difference. Another may be particle shape. As shown by Willibald and others (2020), when sphericity (defined as the ratio of particle area projected onto a plane divided by the area of the smallest circle into which the particle fits) is less than unity the AOR increases. In the present experiments, sphericity was not measured. To assess its role and the role of particle size and shape on the AOR of granulated ice more work is needed.

Whether wood ash has the same effect on the AOR of snow is an open question.

5. Conclusion

The addition of a small amount of wood ash doubles the AOR of granulated ice at −10°C, but has little effect at −30°C. We hypothesize that this behavior may be explained in terms of the freezing of water that is formed at the higher temperature through the reaction of salt within the ash. To test this hypothesis, more work is needed to investigate the role of particle size and shape.

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