TOWARDS AN IMPROVED UNDERSTANDING OF GLIDE-SNOW AVALANCHE RELEASE: INTERFACE SHEAR COLD LABORATORY TESTS

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ABSTRACT: Glide-snow avalanches involve significant volumes of moving snow and present a major challenge to infrastructure in snow-covered mountain regions. Their initiation consists of a sequence of processes that remains poorly understood. It is conceptualized as starting with a loss of friction along the snow-ground interface due to the presence of liquid water. To shed more light on the effect of liquid water at the snow-ground interface on friction, we tested snow samples on a temperature-controlled substratum in a cold laboratory for different conditions of roughness and snow liquid water content (LWC). We performed 51 interface shear tests, analyzed the stress-displacement behavior, and studied the effect of interfacial water on the friction angles (static and kinetic). A sort of stick-slip behavior was observed on lubricated glass. On a dry and rough surface, the snow failed across the sample and no sliding occurred at the interface. Under dry conditions on a smooth surface or lubricated conditions on a rough surface, a strain-softening behavior with an interfacial strength was observed. For the tests where the frictional strength was exceeded, the friction angle, both static and kinetic, showed no dependence on the liquid water content. In the future, we plan to refine and extend the experimental setup to investigate snow compaction and analyze the effect of snowpack properties on gliding behavior.

KEYWORDS: glide-snow avalanche initiation, liquid water content, friction

1. INTRODUCTION

Glide-snow avalanches (a type of full-depth avalanches) involve significant volumes of moving snow. Compared to other types of avalanches, glide-snow avalanches are considered unpredictable and difficult to mitigate, presenting a considerable challenge to protecting roads, railways, ski resorts, and buildings (e.g., Jones, 2004; Simenhois and Birkeland, 2010). Forecasting their activity is vital and requires a solid understanding of the processes involved in the release of glide-snow avalanches.

Glide initiation is conceptualized as starting with a loss of friction along the ground-snow interface due to liquid water accumulation (e.g., McClung and Clarke, 1987). The snow glides mainly on smooth surfaces and under certain snowpack conditions (Newesely et al., 2000). Additional stresses occur at the boundaries of the sliding slab. Tensile stress in the upper part may result in a tensile fracture through the entire depth of the snowpack (glide crack). After a glide crack opens, the snow can continue to glide and stresses increase at the lower end until the compression (retention) zone, fails and the avalanche is released (Bartelt et al., 2012). Not every visual sign of snow gliding (glide crack, buckling or bulges) results in an avalanche. For those that do, the timing between these signs and the avalanche event can vary from hours to weeks, making predictions challenging. However, Fees et al. (2023) have shown that most glide-snow avalanches release within 24 h after glide crack opening. Still, in their study, half of the glide-snow avalanches were released without a visible glide crack that could have served as a precursory signal.

Although glide-snow avalanche activity has been studied since the 1930s, the conditions at the ground-snow interface that promote snow gliding are still largely unknown (Ancey and Bain, 2015; Höller, 2014). Addressing these issues requires high-resolution monitoring of ground and snow properties in space and time (Fees et al., 2024), a better understanding of the water transport across the ground-snow interface (Lombardo et al., 2024), and a better understanding of mechanical properties of wet snow.

We aim to describe the frictional behavior of snow on surfaces of different properties and for varying liquid water content at the interface. To this end, we performed interface shear tests between snow and temperature-controlled surfaces in a controlled environment (SLF cold lab). We analyzed the test results using a classical geotechnical stress-strain approach. We derived static and kinetic friction angles from the stress behavior and studied the influence of liquid water content.

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2. INTERFACE SHEAR TEST

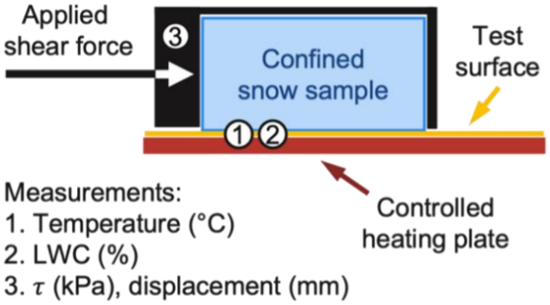

Figure 1: Experimental setup with interface shear test to determine friction coefficients at the interface between snow and impermeable surfaces according to different liquid water content.

To study the effect of the presence of water at the interface and the effect of increasing water content on the coefficients of friction, we designed an interface shear experiment with a temperature-controlled substratum.

Sample preparation

The snow specimen had a diameter of 8 cm and a height of 5 cm. The snow samples were prepared by compressing different types of snow between two 10 mm steel plates at 80 kPa. We used snow samples consisting of either decomposing and fragmented precipitation particles (DF), two samples of rounded grains (RG) or melt forms (MF) (Fierz et al., 2009).

Interface shear test

The interface shear laboratory tests were performed in the SLF cold lab (Figure 1). The cold lab was at a constant temperature of -(2 ± 0.5) °C. To perform a test, a snow specimen was placed in a 3D printed shear box. The inner shear box was a cylinder with a diameter of 8 cm and a height of 4.7 cm to ensure clearance between the shear box and the ground surface. The outer shear box had one flat side to ensure parallel contact with the shearing device. When the specimen was ready to be tested, the substratum surface on the shear path was dried and cleaned using isopropanol alcohol, the specimen was placed on the shear path and the force was applied immediately without delay. The first version of this test was a displacement-controlled test where the applied horizontal force was measured using a snow micro-penetrometer (SMP; Schneebeli and Johnson, 1998). Measurements were stopped after 8 mm of horizontal displacement. A constant confining normal stress of 434 Pa was applied vertically to the specimen. The interface shear tests were conducted on two different surfaces, glass and waterproof sandpaper grain 220.

Liquid water content measurement

To determine the liquid water content (LWC), we measured dry snow density and the relative permittivity using a capacitive sensor (SLF snow sensor) (Denoth, 1994). Immediately after every shear test, the relative permittivity of the snow sample was measured five times. We applied a 70°-rotation between each of the five measurements and calculated the mean and standard deviation.

Dry and wet conditions

Two testing conditions were distinguished. First, dry conditions, where the environment, the snow sample, and the surface were kept at a constant temperature of -2 °C. Second, wet conditions, where the surface was heated to a positive controlled temperature of 2 °C for a defined duration, which changed the LWC.

Supplementary measurements

Additional measurements were made during the experiments to complement the stress-displacement and LWC data. The microstructure of the four different types of snow tested was characterized by using micro-computed tomography (µCT) imaging to determine density. Four tests were filmed with a high-speed camera and the surface temperature of the substratum was recorded during the tests.

3. RESULTS

Shear stress – horizontal displacement behaviors

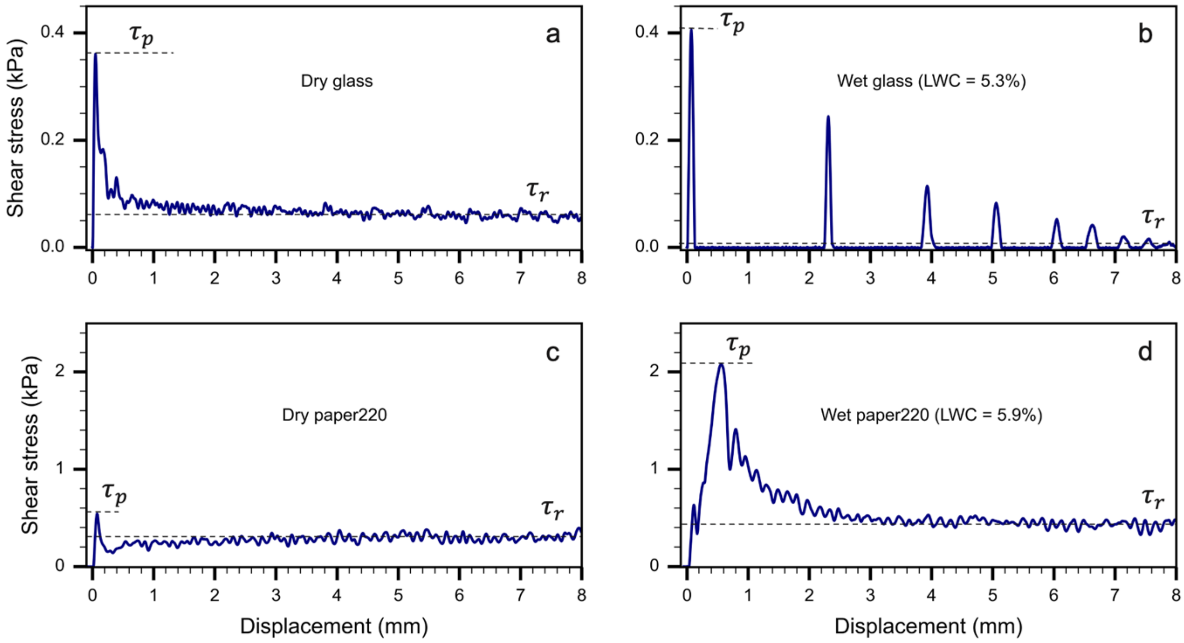

Figure 2: Shear stress as a function of horizontal displacement for (a,c) dry and (b,d) wet conditions on two different surfaces: (a,b) glass and (c,d) sandpaper grain 220.

We analyzed the stress behavior of 51 interface shear tests: 14 under dry conditions (11 on glass surface and 3 on sandpaper grain 220), and 37 were performed in wet conditions (26 on glass surface and 11 on sandpaper grain 220). Under wet conditions, the LWC varied from 0.1% to 11%. From the stress-displacement curves, we determined the peak shear stress (shear strength, τ_p) and the residual shear stress τ_r. The normal stress (σ_n) was calculated from the confining stress, specimen density and volume.

A typical softening curve was recorded under dry conditions on the glass surface and under wet conditions on the sandpaper (Figure 2a, d). In these curves, the shear stress increased up to the interface shear strength τ_p, then it decreased to a constant residual shear stress value τ_r Under wet conditions on the glass surface (Figure 2b), all tests exhibited a behavior resembling the stick-slip phenomenon. The shear stress alternated between increasing stress up to a peak (stick) and a low value (slip), with the peak stress decreasing with increasing horizontal displacement. The shear stress reached its residual value after a large displacement (>10 mm, not shown). In dry conditions and on a rough surface (Figure 2c), the failure occurred within the snow sample and not at the interface indicating that the frictional strength was higher than the snow strength.

Angles of friction

We calculated the static and kinetic friction angles for the 51 experiments as a function of LWC. The ratio of the peak shear stress to the normal stress is defined as the coefficient of static friction $\mu_\mathrm{s} = \tau_\mathrm{p}/\sigma_\mathrm{n}$. The ratio of the residual shear stress to the normal stress is defined as the coefficient of kinetic friction $\mu_\mathrm{k} = \tau_\mathrm{r}/\sigma_\mathrm{n}$. The corresponding friction angles are given by the inverse tangent of these coefficients. The tests under dry conditions on a rough surface are not shown as the failure occurred within the snow samples and not at the interface with the substratum.

On glass, there was no trend in friction angles with LWC (Figure 3). The static friction coefficients were relatively scattered, with an average value of (33±7)°.The average kinetic friction angle was low: 2.7°.

Friction angles were higher on rough surfaces than on smooth glass surfaces ($\phi_s = 68° \pm 8°$), but again there was no clear trend with LWC.

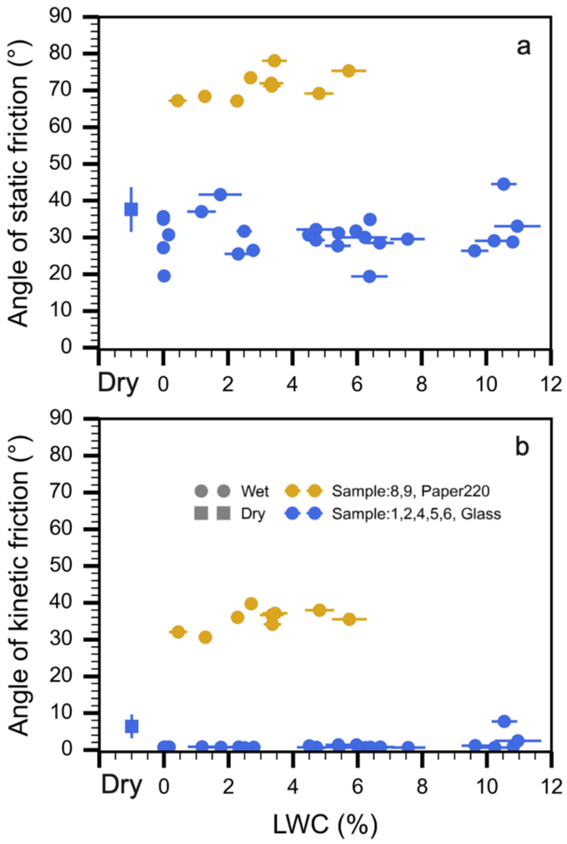

Figure 3: Interface shear test results for four types of snow on glass and sandpaper surfaces. (a) Angle of static friction and (b) angle of kinetic friction as a function of liquid water content under wet and dry conditions.

4. DISCUSSION AND SUMMARY

We investigated the effect of liquid water on static and kinetic friction with the liquid water content at the snow-substratum interface. We developed an interface shear test setup with a temperature-controlled substratum to control the amount of liquid water at the interface between the snow sample and the substratum. Tests were performed on glass and sandpaper under dry and wet conditions. Interestingly, the friction angles did not show a dependence on the liquid water content.

The interface shear test results revealed different failure behaviors in line with, for instance, observations between soil and steel (Tsubakihara et al., 1993). For tests performed on a rough and unlubricated surface (dry condition), the failure occurred within the snow sample. On a lubricated or smooth surface, failure occurred at the interface and the behavior can be represented by a Mohr-Coulomb slip model. To shed more light on this differing behavior, the influence of confining normal stress should be investigated in more detail.

Yamanoi and Endo (2002) reported that the shear strength of snow decreased with liquid water content, whereas our tests did not show a dependence of interface strength on liquid water content.

On lubricated glass, all tests showed a behavior that resembles the stick-slip phenomenon. Shortly after starting the test, with little displacement, the stress sharply increased up to the interface shear strength. Then, sliding started and as the SMP rod lost contact with the specimen, the stress dropped. When the SMP rod got in contact again, the stress increased again, until the sliding motion started again. This peculiar behavior may be due to capillary bridges and/or surface tension.

In conclusion, the results of the direct shear testing on different surfaces demonstrate that the failure behaviors observed depend on the amount of interfacial liquid water content and surface roughness. However, we did not observe decreasing frictional strength with increasing LWC. Further experiments are needed to analyze the reasons and confirm these preliminary findings.

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