Review 1 (by anonymous referee)

Dear referee,
we thank you very much for your interesting, constructive and valuable suggestions and comments related to the content and editorial issues. We carefully addressed all of them and listed the changes in detail hereafter.

Philipp Mamot, on behalf of all co-authors

RC = Referee comment
AR = Author response

Line 55/Figure 1:
RC: “Also give the coordinates of the Zugspitze location”
AR: As suggested by the referee, we provided the coordinates of the Zugspitze location in the text (lines 59-61 in the revised manuscript):
“The limestone samples used for the precedent laboratory tests by Mamot et al. (2018), to which this study refers, were picked from the Zugspitze (47°25’21" N,10°59’13" E, 2900 m a.s.l.), Germany.”

Line 65:
RC: “Sample preparation: Please comment on the alignment of mica parallel to the surfaces of the samples used in the experiments: presumably the samples were cut parallel to the foliation. How does the mica content on the sample surface compare with the mica content in the thin sections? Were the samples cut through mica-rich bands (weak bands and therefore more likely to form fractures in a rock mass)? How many samples were prepared and what was the variation of these samples in terms of mica content?”
AR: We revised the information on the sample preparation and the mica content. A part of the text was shifted from Sect. 2.1 to the second paragraph of Sect. 2. in the following way (lines 62-69 in the revised manuscript):
“A thin section analysis was added to the direct shear tests to determine the mineral composition and the amount of mica in the rock samples. The thin sections were taken from the same rock blocks from which the cylinders for the shear tests were cored. Two thin sections were prepared of each, the gneiss and the mica schist; the results were averaged per rock type. One thin section was produced of the limestone. To account for the anisotropic nature of both gneiss and mica schist, all samples (Sect. 2.1 and 2.2) were prepared from

cuts parallel to the foliation of the rocks. As such, we assume a similar mica content for both the thin sections and the sample surfaces in the shear tests.
[…]
2.1 Petrographical analysis
The thin section analysis was conducted through cross polarised light microscopy with an Olympus DP26 microscope..."

As we only prepared two thin sections per rock type, we cannot give a variation in terms of the mica content.
However, we expanded the supplementary material (xlsx.-file) by the measured mineral compositions of the rock types used for the laboratory tests. This novelty was added to the section "Data availability" (lines 163-164 in the revised manuscript):
*"Data availability. All data which refer to the test conditions and samples, as well as the measured shear stress values and mineral compositions, are provided in the Supplements in a *.xlsx file."*

Line 68-69:
RC: "A strain rate is compared with an acceleration. Please make sure that you compare like for like."
AR: We changed the related sentence as follows (line 77-78 in the revised manuscript):
"(iii) We applied a constant strain rate of $5\times10^{-3}s^{-1}$ provoking brittle fracture of ice and thereby representing the well-advanced stage of rock slope failure."

Line 83:
RC: "I suggest to replace "stronger polarity" with "higher concentration of negative surface charges"."
AR: We modified the wording as proposed (line 94 in the revised manuscript).

Line 94:
RC: "Replace "rock-ice" with "concrete-ice"
AR: We exchanged the wording as proposed (line 105 in the revised manuscript).

Figure 2 and Figure A1:
RC: "I recommend to include the limestone data points from Figure A1 into Figure 2, as this makes it easier for the reader to directly compare the data. It may become necessary to increase the size of Figure 2."
AR: We combined both figures as suggested by the reviewer. For this, we also changed the caption of Fig. 2:

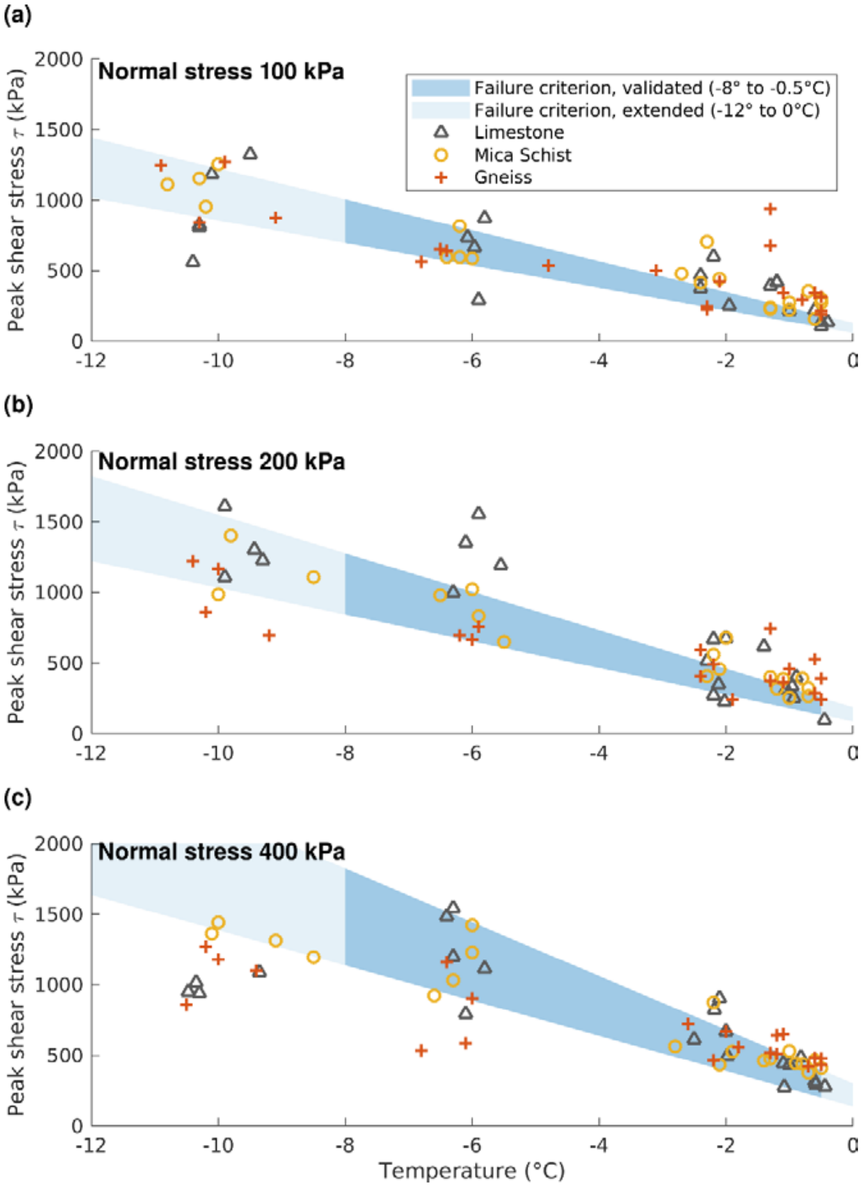


Figure 2. *Peak shear strength across sub-zero temperature of ice-filled rock joints constituted of gneiss (red crosses), mica schist (orange circles) and limestone (grey triangles). The relationships are plotted for normal stresses of a) 100 kPa, b) 200 kPa and c) 400 kPa. The limestone data are added from previous tests by Mamot et al. (2018). The validated range of the failure criterion by Mamot et al. (2018) is marked in dark blue while an extended section to −12 °C and to 0 °C is displayed in light blue.*

Further, we modified the in-text-link to Fig. A1 as follows (line 105 in the revised manuscript): *“This pattern is also visible in the previous tests with limestone (grey triangles in Fig. 2) and…”*

Figure 3:
RC: “Please add a comment on the reliability of the data: how was the failure type observed? Can you give an error estimate for the failure type identification?”

AR: We added a short comment on this in the methods Section 2.2 (line 81-83 in the revised manuscript):
"As in the tests by Mamot et al. (2018), the type of failure was identified qualitatively by visual inspection of the failure surfaces immediately after removing them from the shear apparatus. Samples which did not allow a definite failure type classification were assigned to the mixed failure."

Lines 129-132:
RC: "Point (i): Please comment on the alignment of mica parallel to the surfaces of the samples used in the experiments: natural rock fractures form along mica platelets that are not perfectly parallel. A cut rock surface therefore will expose cuts through a mica grain rather than the surface of the silica sheet. Can you give an estimate how the surface charges of a cut surface differ from the surface charges of a natural fracture?"
AR: The missing information was provided as follows (lines 141-143 in the revised manuscript):
"(i) They are foliated and have typically a high amount of mica aligned subparallel within major shear planes. This property and the resulting effect of the surface charge are expected to be more emphasised along natural joints than along the tested surfaces, as these were cut within intact rock samples."

Lines 129-132:
RC: "Point (ii): I agree with the statement; however, in your experiments you use surfaces with the same roughness. Can you comment on the effect of the different surface roughness on the shear strength of natural joints in limestone vs. joints in gneiss or mica schist?"
AR: We expanded Point (ii) by the following information on the effect of a different rock type-dependent surface roughness on the shear strength of natural joints (lines 144-149 in the revised manuscript):
"(ii) The platy and subparallelly aligned mica grains lead to a very low surface roughness potentially reducing the shear strength. This effect will become more relevant at temperatures close to 0 °C where we observe a higher proportion of fractures along the rock-ice interface. As it is hard to define a representative surface roughness for typically diverse natural fractures, and to guarantee reproducibility of the laboratory rock surfaces, we standardised the joint surface roughness in our tests. Therefore, we assume the effect of varying surface roughness and its dependence on the rock type to be visible in natural fractures, but not in our tests."

Lines 129-132:
RC: "Point (iii): I suggest to replace "presumably" with "possibly". Please comment to what

extent the reduction of shear strength from (ii) and the increase of shear strength from (iii) cancel each other out."

AR: We exchanged the wording from "presumably" to "likely" (line 150 in the revised manuscript).

Further, we added a short comment on how the reduction of shear strength from (ii) and the increase of shear strength from (iii) cancel each other out (lines 150-154 in the revised manuscript):

"(iii) The strong negative surface charge results in an elevated adhesion and equilibrium freezing point which likely leads to a higher peak shear strength.

Due to the uniform surface roughness in the presented tests, we are not able to determine the extent to which the reduction in shear strength by a lower surface roughness (see ii) may offset the increase in shear strength by a strong negative surface charge (see iii). But, overall, we expect the observed mica-dependent higher shear strength close to 0 °C to be suppressed slightly."

Line 136:

RC: "I suggest to replace "systematic increase" with "slight increase". The highest points of the data clouds of the silica samples are higher than the highest points of the limestone samples; however, the data clouds overlap and about half of the limestone data points are also above the failure criterion."

AR: We exchanged the wording as proposed by the referee (line 158 in the revised manuscript).

Review 2 (by Lukas U. Arenson)

Dear Lukas Arenson,
we thank you very much for your constructive and valuable suggestions and comments related to the content and editorial issues. We carefully addressed all of them and listed the changes in detail hereafter.

Philipp Mamot, on behalf of all co-authors

RC = Referee comment
AR = Author response

Lines 2-5:
RC: The referee suggested to
1. write “rock types” instead of “rocks”
2. delete “now”
3. replace “experiments” with “laboratory tests”
4. add a comma
5. add “at temperatures” and “normal stress of”

AR: We adjusted the proposed changes in the revised manuscript as follows (lines 2-5 in the revised manuscript):
“To test the applicability to other rock types, we conducted laboratory tests with mica schist/gneiss, which provide the maximum expected deviation of lithological effects on the shear strength due to strong negative surface charges affecting the rock-ice interface. Retesting 120 samples at temperatures from −10 to −0.5 °C and normal stress of 100 to 400 kPa,…”

Line 8:
RC: The referee suggested to delete “the” and “of” and modify “change” to “changes”.
AR: Adjusted as proposed (line 8 in the revised manuscript).

Line 22:
RC: The referee asked for a reference to the Mohr-Coulomb failure criterion.
AR: We added the reference in the text and included the two citations in the reference list (line 22 in the revised manuscript):

“The failure criterion is based on Mohr-Coulomb (a combination of Coulomb (1776) and Mohr (1900)), and contains a temperature- and stress-dependent cohesion and friction which decrease upon warming.”

Line 25:
RC: The referee replaced “for” with “by” and “the“ with “their”.
AR: We changed the wording as proposed (line 28 in the revised manuscript).

Line 26:
RC: “rock type” was added, “in” was modified by “with”, “laboratory tests” was proposed for “experiments”.
AR: Adjusted as proposed (line 29 in the revised manuscript).

Lines 27-28:
RC: “You mean the rock types in which failure occurred? Sentence unclear.”
AR: We revised the sentence to clarify what we aimed to say (lines 29-31 in the revised manuscript):
“An inventory of rock slope failures in the central European Alps by Fischer et al. (2012) shows that the rock types, in which failure occurred and which potentially include the fracturing of ice-filled rock joints, are not only limestone but also gneiss and granite.”

Line 29:
RC: The referee suggested to add “for the area”.
AR: Adjusted as proposed (line 33 in the revised manuscript).

Line 33:
RC: The referee suggested to add “types”.
AR: Changed as proposed (line 36 in the revised manuscript).

Line 44:
RC: The reviewer suggested to exchange “we” by “one would”.
AR: Adjusted as proposed (lines 47-48 in the revised manuscript).

Caption Fig. 1:
RC: “Use same fonts and subscript as in Figure.”
AR: We revised the caption as followed:

“…b), c) and d) Associated results of thin section analyses, where M refers to mica, Q to quartz, F to feldspar, C to calcite (C_F = fine grains; C_C = coarse grains) and O to others.”

Line 61-62:
RC: The reviewer replaced “due to” with “for a” and the syntax of a sentence was changed.
AR: We realised the proposed changes in the following way (lines 71-72 in the revised manuscript):
“Two point-counter tracks of at least 100 points were indexed on each thin section. We estimated the mica content on sample surfaces via image histogram analysis.”

Line 66:
RC: The reviewer added an “s” at the end of ”piece“.
AR: Modified as proposed (line 75 in the revised manuscript).

Line 70:
RC: The reviewer suggested to add ”respectively“.
AR: Adjusted as proposed (line 80 in the revised manuscript).

Line 83:
RC: The reviewer suggested to exchange “are” with ”is“.
AR: Adjusted as proposed (line 95 in the revised manuscript).

Line 88:
RC: The referee reminded to set “laboratory tests” instead of “experiments”
AR: We exchanged the wording as proposed by the reviewer (line 99).

Lines 90-96:
RC: The referee suggested to

(1) add a comma
(2) write “close to” instead of “close around”
(3) delete “well”
(4) write “outside the valid temperature range proposed” instead of “outside of its proposed valid temperature range”
(5) relocate a part of the sentence to the end of it
(6) replace “visible” with “noted”
(7) add “the”

(8) extend “close to the melting point” with “of the ice”.

AR: Revised as proposed (lines 101-108 in the revised manuscript):

“Overall, the measured peak shear stresses of this study lie well within, or close to the range of the failure criterion (dark blue area in Fig. 2). Even the laboratory tests conducted at −10 °C fit mostly within the expected values of the same failure criterion, although they are outside the valid temperature range proposed. Nevertheless, the measured peak shear stresses tend to fall below the failure criterion for the same temperature and at a normal stress of 400 kPa. This pattern is also noted in the previous tests with limestone (grey triangles in Fig. 2) and in the concrete-ice shear experiments by Günzel (2008), possibly due to the beginning transition from brittle to ductile failure with higher rock overburden leading to a lower shear strength (Renshaw and Schulson, 2001). When approaching the melting point of the ice, above −2 °C, the measured peak shear stresses slightly exceed the calculated range of the failure criterion.”

Line 98 and 101:

RC: “I suggest to use ratio instead of proportion (also in the Figure). To me ratio sounds more natural.”

Further, the reviewer asked to add “of ice” behind “ the melting point”.

AR: Adjusted in the text (line 109 in the revised manuscript), in Fig. 3 and in the respective caption (see below), as proposed.

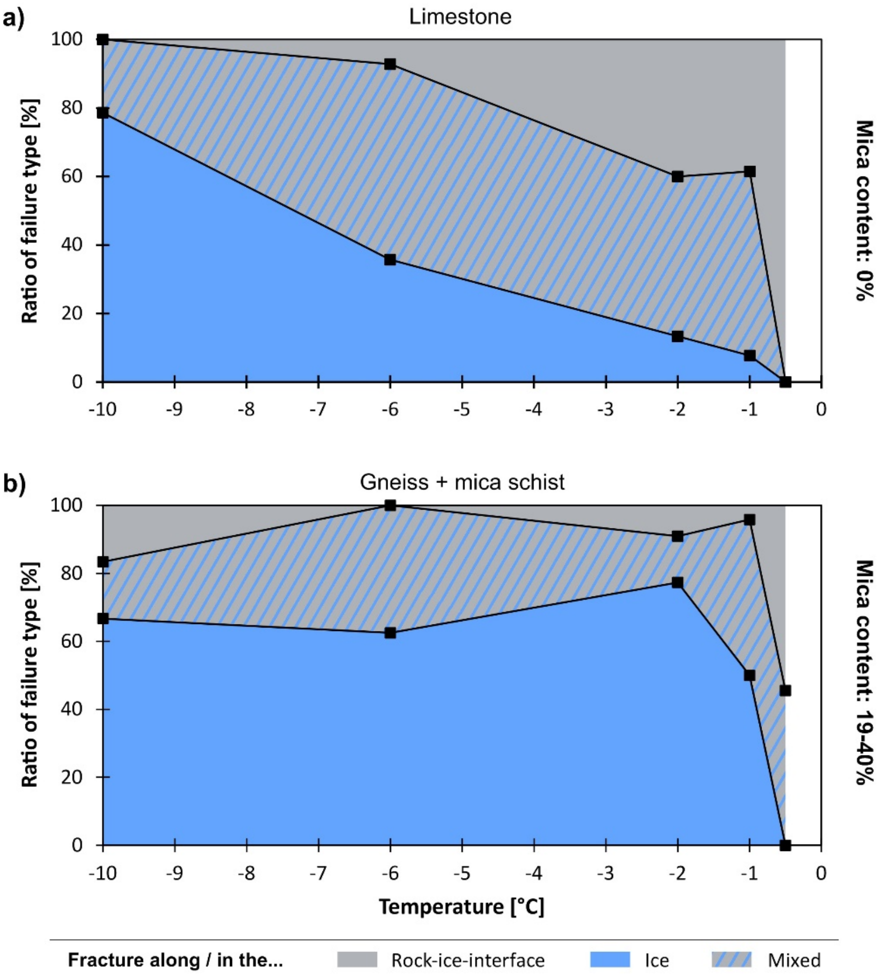


Figure 3. Ratios of failure types versus temperature for a) mica-free (0 %) and b) mica-rich (19-40 %) surfaces in ice-filled rock joints. […] in mica-free joints the proportion of ice fracturing decreases gradually when approaching the melting point of ice…"

Lines 105-109:

RC: The referee suggested to

1. relocate the word "other" behind "rock types"
2. write "demonstrated" instead of "showed"
3. replace "involved in rock slope failures within the Alpine mountain permafrost belt" with "involved in permafrost rock slope failures"
4. write "for those rock types" instead of "to these rocks"
5. exchange "as" by "since"
6. write "below" instead of "to".

AR: Adjusted as proposed (lines 116-120 in the revised manuscript).

Lines 110-117:

RC: The referee suggested to

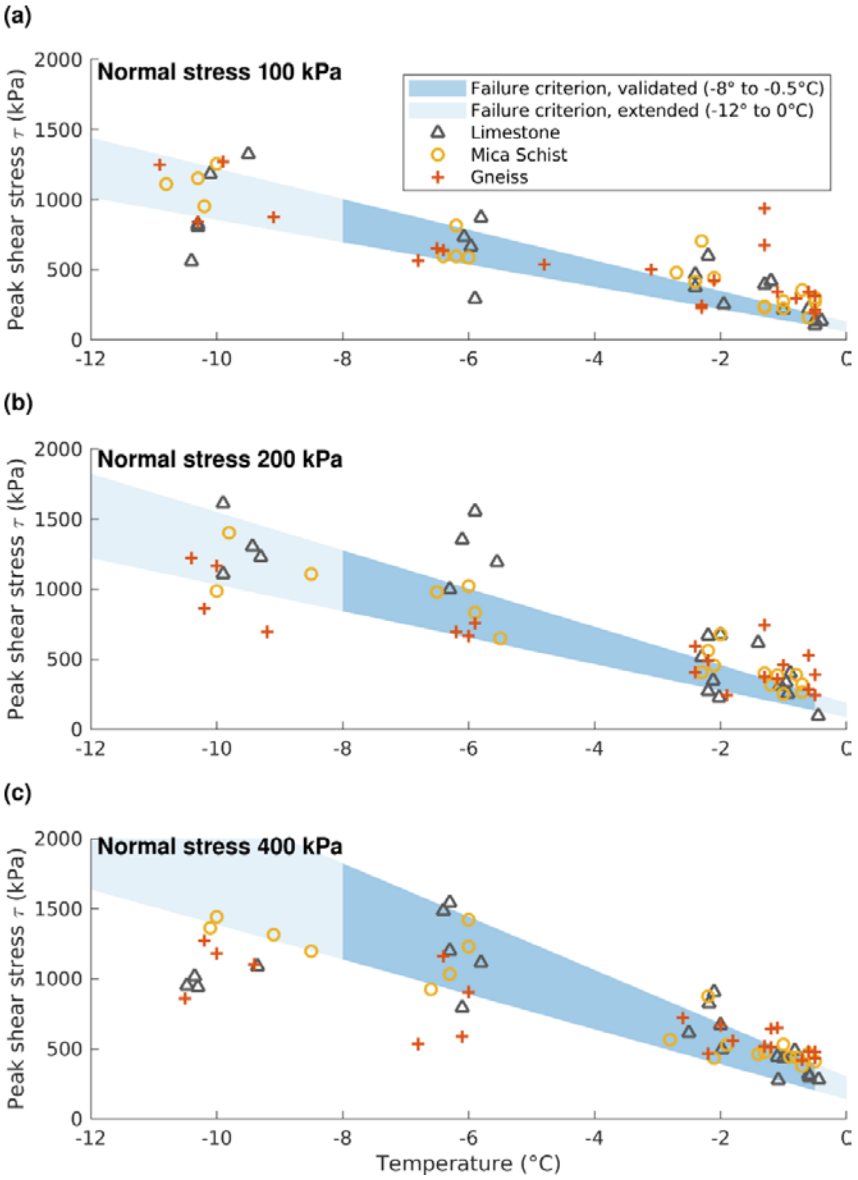
(1) add a comma
(2) write “seems to be” instead of “is rather”
(3) exchange “below” by “to”
(4) extend “close to the melting point” with “of the ice”
(5) delete a reference to Section 1
(6) write “strengthening” instead of “stabilising”.

AR: Revised as suggested by the referee (lines 121-127 in the revised manuscript).

Fig. 2:

RC: The reviewer asked to change the three sub-headings from “normal load” to “normal stress”.

AR: Adjusted as proposed (see below):



Caption of Fig. 2:
RC: “But also an extension from -0.5 °C to 0 °C?”
AR: We added the information that the extended section also refers to temperatures between -0.5 and 0 °C:

“…The validated range of the failure criterion by Mamot et al. (2018) is marked in dark blue while an extended section to −12 ◦C and to 0 ◦C is displayed in light blue.”

Lines 118-119:
RC: “Just be consistent to talk about interface, not contact”
Further, the referee suggested to change the sentence to “…gains in importance at temperatures warmer than -6 °C”
AR: Adjusted as proposed (lines 129-130 in the revised manuscript).

Line 127:
RC: The reviewer added “in the Alps”.
AR: Adjusted as proposed (line 138 in the revised manuscript).

Caption of Fig. 3:
RC: The reviewer added “of ice” to “the melting point”.
AR: Adjusted as proposed.

Line 129:
RC: The referee added “rock types”.
AR: Adjusted as proposed (line 140 in the revised manuscript).

Line 132:
RC: “More out of curiosity and for reference to put this into perspective, what is the shear strength (or if not available he UCS) of the unfrozen rocks?”
AR: We provided two sentences on the shear strength of unfrozen joint surfaces to Section 1 (lines 23-26 in the revised manuscript). The presented unfrozen values by Krautblatter et al. (2013) are based on the same normal stresses (100-400 kPa) and on the same rock type (Wetterstein limestone) which were used in the laboratory tests by Mamot et al. (2018). The surface roughness of the unfrozen samples (grit of 24 grains per inch) differed only slightly from the one of the ice-filled samples (grit of 80 grains per inch). Shear strength values of

unfrozen gneiss or mica schist surfaces were not available and, hence, could not be presented. The new information in the article is as follows:

"When warming from -1 or -0.5 °C leads to thawing and a subsequent loss of the ice infill, the shear strength of unfrozen joints reduces slightly by approximately 100 kPa (Krautblatter et al., 2013; Mamot et al., 2018). However, the unfrozen shear strength is 400-1000 kPa lower when compared with the one of ice-filled joints at temperatures between -2 and -10 °C."

Lines 134-140:

RC: The referee proposed to

1. change "performed" into "carried out"
2. write "laboratory tests" instead of "experiments"
3. replace "of" by "in", "existence" by "presence" and "lie" by "correspond"
4. add "introduced by"
5. replace "mostly all rock types" by "wide variety of rock types"
6. add "in the Alps" at the end of the sentence

AR: Adjusted as proposed (lines 156-162 in the revised manuscript):

"In this study, we carried out 120 constant strain rate shear tests on ice-filled joints in gneiss and mica schist to investigate a potential influence of metamorphic foliated rocks with high amount of mica on the shear resistance of ice-filled discontinuities. Based on the laboratory tests, we could demonstrate a slight increase in peak shear strength at temperatures close to 0 °C, which is most likely caused by the presence of mica. However, overall our data correspond well with the failure criterion for ice-filled rock joints introduced by Mamot et al. (2018). As the tested mica-rich rocks represent the expected maximum deviation of potential lithological effects on the shear strength, we conclude that the failure criterion is transferable to a wide variety of rock types relevant for permafrost rock slope failures in the Alps.

Brief communication: The influence of mica-rich rocks on the shear strength of ice-filled discontinuities

Philipp Mamot[1], Samuel Weber[1], Maximilian Lanz[1], and Michael Krautblatter[1]

[1]Chair of Landslide Research, Technical University of Munich, Munich, Germany

Correspondence: Philipp Mamot (philipp.mamot@tum.de)

Abstract. A temperature- and stress-dependent failure criterion for ice-filled rock (limestone) joints was proposed in 2018 as an essential tool to assess and model the stability of degrading permafrost rock slopes. To test the applicability to other ~~rocks, we now conducted experiments~~ rock types, we conducted laboratory tests with mica schist/gneiss, which provide the maximum expected deviation of lithological effects on the shear strength due to strong negative surface charges affecting the rock-ice interface. Retesting 120 samples at temperatures from -10 to $-0.5°\,\mathrm{C}$ and normal stress of 100 to $400\,\mathrm{kPa}$, we show that even for controversial rocks the failure criterion stays unaltered, suggesting that the failure criterion is transferable to mostly all rock types.

1 Introduction

~~The climate-related change of~~ Climate-related changes in the thermal conditions in steep bedrock permafrost can lead to rock slope destabilisation or failure (e.g. Gruber and Haeberli, 2007) potentially triggering large scale hazards via process chains (Huggel et al., 2012). A number of failures in bedrock permafrost have exposed residual ice at their shear and detachment planes (Keuschnig et al., 2015; Phillips et al., 2017; Ravanel et al., 2017; Weber et al., 2018; Walter et al., 2020). These observations indicate the occurrence of ice-filled rock discontinuities and their importance as controlling factor for the stability of degrading permafrost rock slopes. While the shear strength of rock joints can be increased by ice fillings due to adhesion and rock-ice-interlocking (Gruber and Haeberli, 2007), warming can reduce the strength of ice-filled joints (Krautblatter et al., 2013). To improve attempts to accurately assess the stability of rock slopes with degrading permafrost due to climate change, we will have to better understand the effect of warming on the shear strength of ice-filled joints.

So far, the shear failure of ice-filled rock joints has been studied in a number of direct shear tests using samples of concrete and ice (Davies et al., 2000; Günzel, 2008). Mamot et al. (2018) added a series of constant strain shear tests with real rock samples. The ice-filled rock joints were represented by "sandwich"-like limestone-ice-limestone samples. Normal stresses of 100, 200 and $400\,\mathrm{kPa}$ were applied to the ice-filled discontinuities, which simulated rock overburdens of 4, 8 and $15\,\mathrm{m}$, respectively. A brittle failure criterion was developed for these overburdens and validated for rock temperatures from -8 to $-0.5°\,\mathrm{C}$. The failure criterion is based on Mohr-Coulomb (a combination of Coulomb (1776) and Mohr (1900)), and contains a temperature- and stress-dependent cohesion and friction which decrease upon warming. When warming from -1 or $-0.5°\,\mathrm{C}$ leads to thawing and a subsequent loss of the ice infill, the shear strength of unfrozen joints reduces slightly by approximately

$100\,\mathrm{kPa}$ (Krautblatter et al., 2013; Mamot et al., 2018). However, the unfrozen shear strength is $400-1000\,\mathrm{kPa}$ lower when compared with the one of ice-filled joints at temperatures between -2 and $-10^{\circ}\,\mathrm{C}$.

Mamot et al. (2018) postulate that their failure criterion can be applied to shear planes in all rock types, even though they solely used limestone ~~for the~~ in their laboratory experiments. The authors discussed potential influences of the rock type on the shear strength and they emphasised the need to study a potential ~~dependency in additional experiments~~rock type dependency with additional laboratory tests. An inventory of rock slope failures in the central European Alps by Fischer et al. (2012) shows that the rock types, ~~which are potentially involved in the fracture~~ in which failure occurred and which potentially include the fracturing of ice-filled rock joints, are not only limestone but also gneiss and granite. Most of the detachment zones are likely affected by permafrost and roughly follow the assumed lower altitudinal boundary of permafrost for the respective area. Rock slopes within this boundary are expected to respond sensitively to warming and a related reduction in stability (Nötzli et al., 2010), and predominantly consist of gneiss, limestone or schist at altitudes from $2000-3000\,\mathrm{m\ a.s.l.}$ and mostly of gneiss or granite at altitudes $>3000\,\mathrm{m\ a.s.l.}$ (Fischer et al., 2012).

Among the ~~rocks~~ rock types observed to be involved in permafrost rock slope failures, gneiss and schist are metamorphic rocks with a pronounced foliation and typically show bands with a concentrated abundance of aligned, platy mica. These bands can form weak zones where shear planes develop more easily (Shea and Kronenberg, 1993). Furthermore, basal cleavage surfaces of mica carry a strong negative surface charge compared to other minerals like quartz, feldspar or calcite. When in contact with water, this leads to the formation of a common but specifically strong electrical double layer (Fenter et al., 2000; Bourg and Sposito, 2011). Such an electrical double layer causes a homogenous alignment of at first water molecules, and, with freezing, structural integrity in ensuing ice crystals (Dosch et al., 1996). As a result, adhesion at the interface is increased and the process of phase change upon warming is delayed. While the mean equilibrium freezing point in permafrost rocks is depressed to $-0.7\pm0.4^{\circ}\,\mathrm{C}$ (Krautblatter, 2009), mica-rich rocks with strongly attractive surfaces are observed to increase the freezing temperature (Alba-Simionesco et al., 2006). Close below the melting point, this results in a crystalline contact layer on mica-rich surfaces while inner layers remain fluid. In contrast, a liquid layer forms along the rock-ice interface on weakly attractive silica-rich surfaces while the absorbed water in the mineral is crystalline (Alba-Simionesco et al., 2006). Consequently, ~~we~~ one would theoretically expect a stronger adhesion at the rock-ice interface for mica-rich rocks, presumably leading to a higher shear strength close below $0^{\circ}\,\mathrm{C}$.

Therefore, this study aims to verify if the failure criterion by Mamot et al. (2018) accounts for (i) the relevance of gneiss for permafrost rock slope failures, (ii) the abundance of gneiss and schist within the lower permafrost boundary and (iii) the potentially significant effects of foliated metamorphic rocks with high mica content on the shear strength of ice-filled joints. ~~Hence, thismanuscript addresses~~ For this, we performed 120 shear tests on ice-filled joints in gneiss and mica schist rerunning the sample preparation, test setup and procedure of Mamot et al. (2018). In the present article we address the following question: Is the failure criterion for ice-filled rock joints by Mamot et al. (2018) valid for rocks with different mineral composition, specifically containing mica?

2 Methods

Two different rock types with a considerable mica content were selected for this study: gneiss that originates from the Matterhorn (45°58’52" N, 07°40’14" E, 3218 m a.s.l.), Switzerland, and mica schist that was involved in the Ramnanosi landslide, close to the village of Flåm (60°49’41" N, 07°08’59" E, 750 m a.s.l.), Norway (Fig. 1a). The limestone samples used for the precedent laboratory tests by Mamot et al. (2018), to which this study refers, were picked from the Zugspitze (47°25’21" N, 10°59’13" E, 2900 m a.s.l.), Germany.

~~a) Map showing the locations where samples were collected. b), c) and d) Associated results of thin section analyses, where M refers to mica, Q to quartz, F to feldspar, C to calcite (Cf = fine grains; Cc = coarse grains) and O to others.~~

2.1 ~~Petrographical analysis~~

A thin section analysis was ~~conducted~~ added to the direct shear tests to determine the mineral composition and the amount of mica in the rock samples. The thin sections were taken from the same rock blocks from which the cylinders for the shear tests were cored. Two thin sections were prepared of each, the gneiss and the mica schist; the results were averaged per rock type. One thin section was produced of the limestone. To account for the anisotropic nature of both gneiss and mica schist, all ~~thin sections~~ samples (Sect. 2.1 and 2.2) were prepared from cuts ~~perpendicular~~ parallel to the foliation of the rocks. ~~The~~ As such, we assume a similar mica content for both the thin sections and the sample surfaces in the shear tests.

2.1 Petrographical analysis

The thin section analysis was conducted through cross polarised light microscopy with an Olympus DP26 microscope which is standardised according to the DIN ISO 8576 (2002). The proportionate mineral compositions were recorded in a PELCON Automatic Point Counter ~~due to~~ for a point-counter analysis as recommended by Chayes (1949). ~~On each thin section, two~~ Two point-counter tracks of at least 100 points were indexed on each thin section. We estimated the mica content on sample surfaces via image histogram analysis.

2.2 Shear experiments

The sample preparation, setup and procedure of the tests were conducted according to Mamot et al. (2018) to guarantee comparability: (i) Each rock–ice–rock sandwich sample ~~consists of two piece~~ consisted of two pieces of rock with a surface roughness of 80 grains per inch and its gap is filled with a $3.5 \pm 0.5\,\mathrm{mm}$ thin ice layer. (ii) We used the same custom built shear apparatus installed in a temperature-controlled cooling box. (iii) We applied a constant strain rate of $5 \times 10^{-3}\,\mathrm{s}^{-1}$ provoking brittle fracture of ice and thereby representing the ~~final acceleration stage of a~~ well-advanced stage of rock slope failure.

Tests were performed at temperatures of -10, -6, -2, -1 and $-0.5°$ C and at normal stress levels of 100, 200 and 400 kPa, respectively. Four tests were conducted ~~for each~~ per rock type and ~~each~~ per combination of temperature and normal stress, leading to a total of 120 tests. As in the tests by Mamot et al. (2018), the type of failure was identified qualitatively by visual

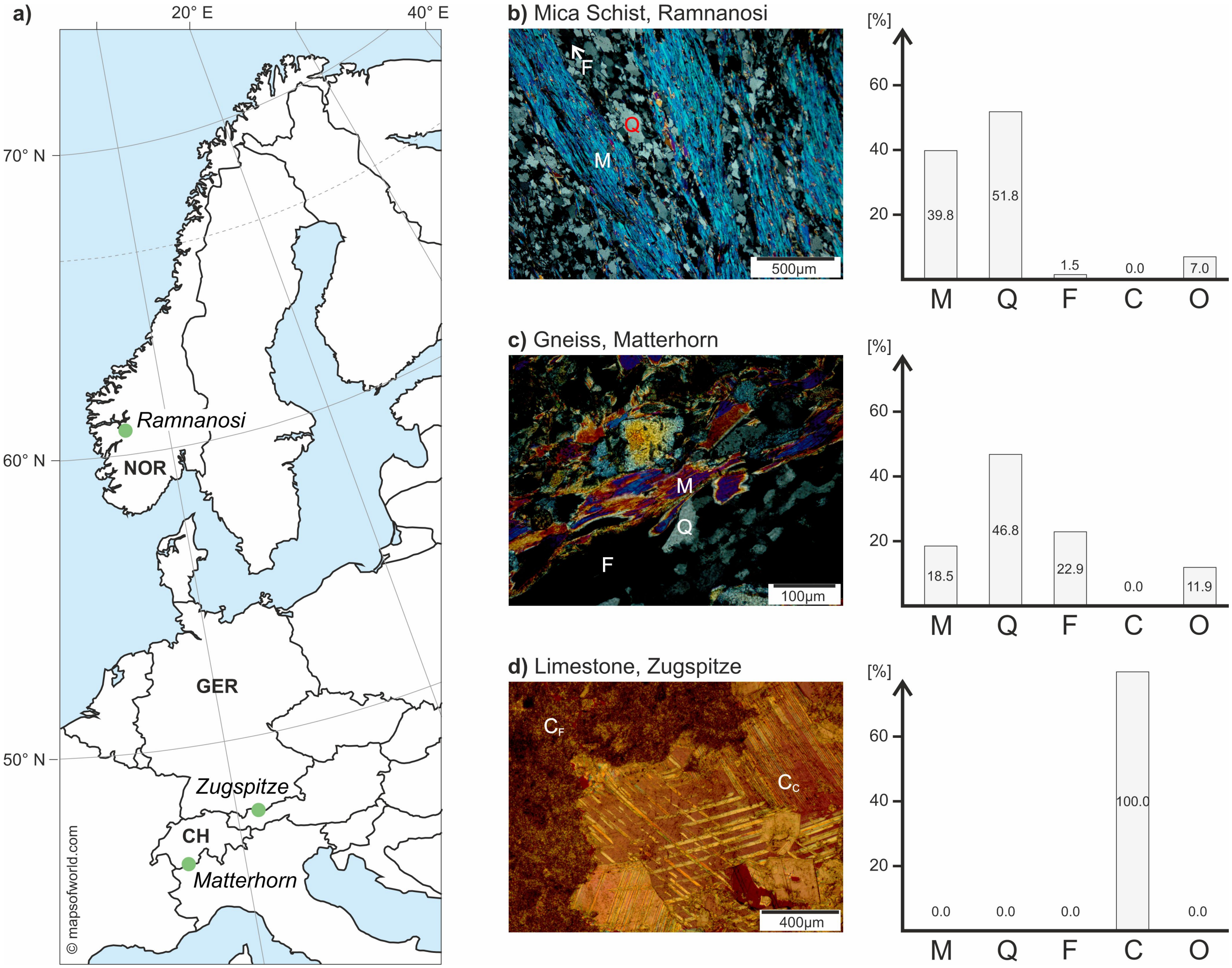


Figure 1. a) Map showing the locations where samples for this study and the previous one by Mamot et al. (2018) were collected. b), c) and d) Associated results of thin section analyses, where M refers to mica, Q to quartz, F to feldspar, C to calcite (C_F = fine grains; C_C = coarse grains) and O to others.

inspection of the failure surfaces immediately after removing them from the shear apparatus. Samples which did not allow a definite failure type classification were assigned to the mixed failure.

3 Results and interpretation

3.1 Mineral composition relevant for rock-ice interfaces

The mica schist is a fine-grained rock with well-developed foliation. Layers of dark mica, predominantly biotite, and light quartz and plagioclase alternate in the rock. In the thin section analysis (Fig. 1b) the mica schist shows very distinct bands of mica (39.8%) in a ground mass mostly comprised of quartz (51.8%). Other minerals identified in the sample are feldspar and chlorite as well as possibly sillimanite and amphibole. An average porosity of 1.3% was determined in the thin section analysis. The gneiss is clearly laminated and shows bands of mica (18.5%), yet it is less distinctly layered than the mica schist (Fig. 1c). The main components are quartz (46.8%) and feldspar (22.9%), other minerals identified in the sample are chloritoid and epidote as well as traces of chlorite, amphibole and rutile. Furthermore, the porosity of the gneiss is considerably low (0.9%, Draebing and Krautblatter, 2012) compared to the mica schist. Both rock types show a high abundance of mica minerals at the sample surfaces presumably leading to a ~~stronger polarity~~ higher concentration of negative surface charges than at limestone surfaces. The latter ~~are~~ is only constituted of calcite without any occurrence of mica (Fig. 1d).

3.2 Shear tests of rock-ice interfaces with mica-rich rocks

Mamot et al. (2018) subdivided the paths of shear stress and shear strain into five distinct stages including (i) consolidation, (ii) adjustment to the sample holder, (iii) buildup of the shear stress, (iv) failure and (v) post-failure behaviour. The same pattern can be identified by the presented ~~experiments~~ laboratory tests with mica-rich rocks. We also observe a general decrease in peak shear stress with increasing temperature from −10 to −0.5° C at all tested normal stress levels, without any systematic difference between the samples of mica schist and gneiss (Fig. 2). Overall, the measured peak shear stresses of this study lie well within~~or close around~~, or close to the range of the failure criterion (dark blue area in Fig. 2). Even the ~~experiments~~ laboratory tests conducted at −10° C fit mostly ~~well~~ within the expected values of the same failure criterion, although they are outside ~~of its proposed~~ the valid temperature range proposed. Nevertheless, ~~for the same temperature and at a normal stress of 400 kPa,~~ the measured peak shear stresses tend to fall below the failure criterion for the same temperature and at a normal stress of 400 kPa. This pattern is also ~~visible~~ noted in the previous tests with limestone (grey triangles in Fig. ~~??~~2) and in ~~rock-ice~~ the concrete-ice shear experiments by Günzel (2008), possibly due to the beginning transition from brittle to ductile failure with higher rock overburden leading to a lower shear strength (Renshaw and Schulson, 2001). When approaching the melting point of the ice, above −2° C, the measured peak shear stresses slightly exceed the calculated range of the failure criterion.

Figure 3 illustrates the temperature-dependent ~~proportion~~ ratio of failure types that were observed in the shear tests for distinguishing rocks with and without mica content. Failure within the ice is very dominant for mica-rich rocks in the temperature range from −10 to −1° C, but absent at −0.5° C. In contrast, rock without mica (limestone) shows a gradual decrease in the

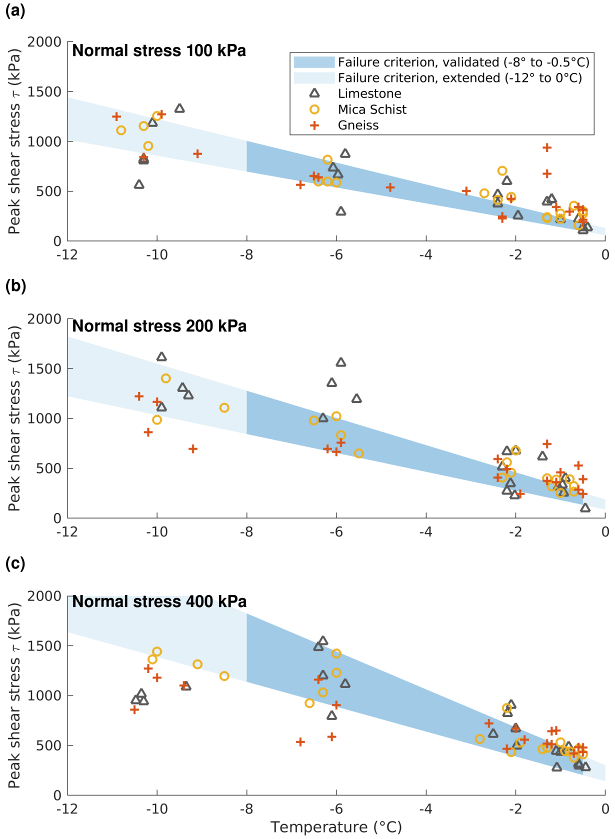


Figure 2. Peak shear strength across sub-zero temperature of ice-filled rock joints constituted of gneiss (red crosses)~~and~~ , mica schist (orange circles) and limestone (grey triangles). The relationships are plotted for normal stresses of a) $100\,\mathrm{kPa}$, b) $200\,\mathrm{kPa}$ and c) $400\,\mathrm{kPa}$. The limestone data are added from previous tests by Mamot et al. (2018). The validated range of the failure criterion by Mamot et al. (2018) is marked in dark blue while an extended section ~~down~~ to -12° C and to 0° C is displayed in light blue.

~~proportion~~ ratio of failure within the ice and a gradual increase in the ~~proportion~~ ratio of failure along the rock-ice interface with warming. Overall, it is remarkable that the fracture along the rock-ice interface and mixed fracture are the only failure types at -0.5° C for limestone and mica-rich rocks.

4 Discussion

In Mamot et al. (2018) the question remained open if the failure criterion for ice-filled rock joints was transferable to ~~other rock types~~ rock types other than limestone. As Fischer et al. (2012) ~~showed~~ demonstrated that gneiss and schist are among the most relevant ~~rocks involved in permafrost~~ rock types involved in rock slope failures within the Alpine mountain permafrost belt, this study aims at testing the applicability of the failure criterion ~~to these rocks~~for those rock types. Furthermore, gneiss

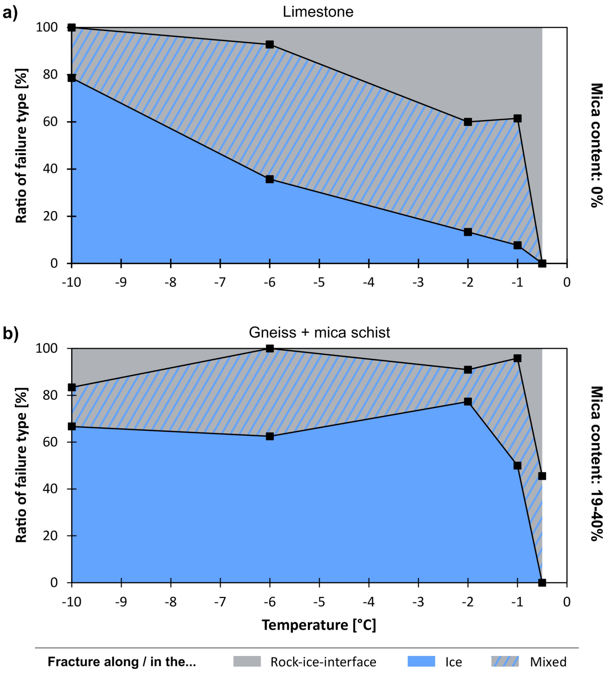


Figure 3. ~~Proportions~~ Ratios of failure types versus temperature for a) mica-free (0%) and b) mica-rich (19-40%) surfaces in ice-filled rock joints. Failure in mica-rich joints is dominated by fracturing inside the ice layer, whereas at temperatures warmer than -1°C failure is controlled by fracturing along the rock-ice interface and the mixed type. However, in mica-free joints the proportion of ice fracturing decreases gradually when approaching the melting point of ice while rock-ice fracturing gains importance, especially at temperatures warmer than -1°C.

and schist were selected~~as~~, since they are characterised by foliation with high mica content, which may potentially affect the shear strength of ice-filled joints close ~~below~~ to 0° C.

We quantified the shear strength of ice-filled discontinuities in mica-rich rocks, which fits well to the temperature- and normal stress-dependent failure criterion (Fig. 2), thereby indicating its validity for mica-rich rocks. It is remarkable that the failure criterion ~~is rather~~ seems to be conservative for conditions close to 0° C compared to the shear tests with mica-rich rocks. However, this underestimation of shear strength does not state a problem for any purpose of rock slope stability assessment and, hence, does not diminish the applicability of the failure criterion. The higher shear strength close ~~below~~ to 0° C for mica-rich rocks has been expected by the authors and may be explained by the higher adhesion at the rock-ice interface, the delayed phase change upon warming and the absence of a liquid layer along mica-rich joint surfaces ~~and~~ close to the melting point ~~(see Sect. 1). The stabilising~~ of ice. The strengthening effect of the rock-ice-contact by mica becomes also evident when looking at the temperature-dependent distribution of failure types (Fig. 3): While in mica-rich rocks failures along the rock-ice ~~contact only dominate above~~ interface only dominate at temperatures warmer than −1° C, in limestone (without mica) the same failure type gradually gains ~~importance upon warming and above~~ in importance at temperatures warmer than −6° C.

Previous publications on the shear strength of ice-filled rock joints relate to a small number of tests on samples with ice and concrete, generally not below -5° C (Günzel, 2008; Davies et al., 2000). Krautblatter et al. (2013) developed a first failure criterion which based on the experiments by Günzel (2008). Five years later, Mamot et al. (2018) proposed an improved failure criterion which refers to rock-ice-rock samples and covers a broader range of bedrock temperatures. This study demonstrates that the failure criterion by Mamot et al. (2018) is surprisingly resilient as it can be applied to (i) different failure types including the fracture in ice and along the rock-ice contact, (ii) a wide range of temperatures relevant for bedrock permafrost (-0.5 to -8° C), (iii) a wide range of relevant stress conditions ($100-400\,$kPa) and (iv) mostly all rock types relevant for permafrost rock slope failures in the Alps, as the metamorphic mica-rich rocks tested in this study represent the expected maximum deviation of potential lithological effects on the shear strength of ice-filled rock joints. This strong deviation is established due to three characteristics of the tested ~~rocks:~~ rock types:

(i) They are foliated and have typically a high amount of mica aligned ~~parallel to the shear surfaces.~~ subparallel within major shear planes. This property and the resulting effect of the surface charge are expected to be more emphasised along natural joints than along the tested surfaces, as these were cut within intact rock samples.

(ii) The platy and ~~parallelly~~ subparallelly aligned mica grains lead to a very low surface roughness potentially reducing the shear strength. This effect will become more relevant at temperatures close to 0° C where we observe a higher proportion of fractures along the rock-ice interface. As it is hard to define a representative surface roughness for typically diverse natural fractures, and to guarantee reproducibility of the laboratory rock surfaces, we standardised the joint surface roughness in our tests. Therefore, we assume the effect of varying surface roughness and its dependence on the rock type to be visible in natural fractures, but not in our tests.

(iii) The strong negative surface charge results in an elevated adhesion and equilibrium freezing point ~~presumably leading~~ which likely leads to a higher peak shear strength.

Due to the uniform surface roughness in the presented tests, we are not able to determine the extent to which the reduction in shear strength by a lower surface roughness (see ii) may offset the increase in shear strength by a strong negative surface charge (see iii). But, overall, we expect the observed mica-dependent higher shear strength close to 0° C to be suppressed slightly.

5 Conclusions

In this study, we ~~performed~~ carried out 120 constant strain rate shear tests on ice-filled joints in gneiss and mica schist to investigate a potential influence of metamorphic foliated rocks with high amount of mica on the shear resistance of ice-filled discontinuities. Based on the ~~experiments~~laboratory tests, we could demonstrate a ~~systematic increase of~~ slight increase in peak shear strength at temperatures close to 0°C, which is most likely caused by the ~~existence~~ presence of mica. However, overall our data ~~lie well within~~ correspond well with the failure criterion for ice-filled rock joints introduced by Mamot et al. (2018). As the tested mica-rich rocks represent the expected maximum deviation of potential lithological effects on the shear strength, we conclude that the failure criterion is transferable to ~~mostly all~~ a wide variety of rock types relevant for permafrost rock slope failures in the Alps.

Data availability. All data which refer to the test conditions and samples, as well as the measured shear stress values and mineral compositions, are provided in the Supplements in a *.xlsx file.

Appendix A

~~Peak shear strength versus sub-zero temperature for ice-filled rock joints constituted of limestone. The presented data are taken from previous tests by Mamot et al. (2018). Relationships are plotted for normal stresses of a) 100 kPa, b) 200 kPa and c) 400 kPa. The validated range of the failure criterion by Mamot et al. (2018) is marked in dark blue while an extended section down to $-12°$ C is displayed in light blue.~~

Author contributions. Philipp Mamot (PM), Samuel Weber (SW) and Michael Krautblatter (MK) designed the shear experiments. Max Lanz (ML) prepared the samples and performed the tests, as well as the thin section analyses. He was supervised by PM and MK. Analysis of the data was conducted by SW, ML and PM. The manuscript was written by PM, SW and ML, with substantial contribution of MK.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We gratefully acknowledge Andreas Grovan Aspaas for providing, coring and cutting the rock samples from Norway. Furthermore, we thank Cordula Bode for preparing the thin sections used for the petrographic analysis. Finally, we thank the Fritz und Lotte Schmidtler-Foundation financing the TUFF fellowship that is held by Samuel Weber.

References

Alba-Simionesco, C., Coasne, B., Dosseh, G., Dudziak, G., Gubbins, K. E., Radhakrishnan, R., and Sliwinska-Bartkowiak, M.: Effects of confinement on freezing and melting, Journal of Physics: Condensed Matter, 18, R15–R68, https://doi.org/10.1088/0953-8984/18/6/r01, https://doi.org/10.1088%2F0953-8984%2F18%2F6%2Fr01, 2006.

Bourg, I. C. and Sposito, G.: Molecular dynamics simulations of the electrical double layer on smectite surfaces contacting concentrated mixed electrolyte (NaCl–CaCl2) solutions, Journal of Colloid and Interface Science, 360, 701 – 715, https://doi.org/https://doi.org/10.1016/j.jcis.2011.04.063, http://www.sciencedirect.com/science/article/pii/S0021979711004991, 2011.

Chayes, F.: A simple point counter for thin-section analysis, American Mineralogist, 34, 1–11, 1949.

Coulomb, C. A.: Essai sur une application des regles de maximis et minimis a quelques problemes de statique, relatifs a l'architecture, Memoires de Mathematique & de Physique, 7, 343–382, 1776.

Davies, M., Hamza, O., Lumsden, B., and Harris, I.: Laboratory measurement of the shear strength of ice-filled rock joints, Annals of Glaciology, 31, 463–467, https://doi.org/10.3189/172756400781819897, 2000.

DIN ISO 8576: Optics and optical instruments - Microscopes - Reference systems of polarized light microscopy, https://doi.org/10.31030/9255520, 2002.

Dosch, H., Lied, A., and Bilgram, J. H.: Disruption of the hydrogen-bonding network at the surface of Ih ice near surface premelting, Surface Science, 366, 43 – 50, https://doi.org/10.1016/0039-6028(96)00805-9, http://www.sciencedirect.com/science/article/pii/0039602896008059, 1996.

Draebing, D. and Krautblatter, M.: P-wave velocity changes in freezing hard low-porosity rocks: A laboratory-based time-average model, The Cryosphere, 6, 1163–1174, https://doi.org/10.5194/tc-6-1163-2012, 2012.

Fenter, P., Cheng, L., Rihs, S., Machesky, M., Bedzyk, M., and Sturchio, N.: Electrical Double-Layer Structure at the Rutile–Water Interface as Observed in Situ with Small-Period X-Ray Standing Waves, Journal of Colloid and Interface Science, 225, 154 – 165, https://doi.org/10.1006/jcis.2000.6756, http://www.sciencedirect.com/science/article/pii/S0021979700967560, 2000.

Fischer, L., Purves, R. S., Huggel, C., Noetzli, J., and Haeberli, W.: On the influence of topographic, geological and cryospheric factors on rock avalanches and rockfalls in high-mountain areas, Natural Hazards and Earth System Sciences, 12, 241–254, https://doi.org/10.5194/nhess-12-241-2012, https://www.nat-hazards-earth-syst-sci.net/12/241/2012/, 2012.

Gruber, S. and Haeberli, W.: Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change, J. Geophys. Res., 112, F02S18, https://doi.org/10.1029/2006JF000547, 2007.

Günzel, F.: Shear strength of ice-filled rock joints, in: Proceedings of the 9th International Conference on Permafrost, Fairbanks, USA, edited by Hinkel, K. M., vol. 1, p. 581–586, 2008.

Huggel, C., Clague, J. J., and Korup, O.: Is climate change responsible for changing landslide activity in high mountains?, Earth Surface Processes and Landforms, 37, 77–91, https://doi.org/10.1002/esp.2223, https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.2223, 2012.

Keuschnig, M., Hartmeyer, I., Höfer-Öllinger, G., Schober, A., Krautblatter, M., and Schrott, L.: Permafrost-Related Mass Movements: Implications from a Rock Slide at the Kitzsteinhorn, Austria, in: Engineering Geology for Society and Territory, edited by Lollino, G., Manconi, A., Clague, J., Shan, W., and Chiarle, M., vol. 1, pp. 255–259, Springer International Publishing, Cham, 2015.

Krautblatter, M.: Detection and quantification of permafrost change in alpine rock walls and implications for rock instability, Ph.D. thesis, Bonn University, 2009.

Krautblatter, M., Funk, D., and Günzel, F.: Why permafrost rocks become unstable: A rock-ice-mechanical model in time and space, Earth Surf. Process. Landf., 38, 876–887, https://doi.org/10.1002/esp.3374, 2013.

Mamot, P., Weber, S., Schröder, T., and Krautblatter, M.: A temperature- and stress-controlled failure criterion for ice-filled permafrost rock joints, The Cryosphere, 12, 3333–3353, https://doi.org/10.5194/tc-12-3333-2018, 2018.

Mohr, O.: Welche Umstände bedingen die Elastizitätsgrenze und den Bruch eines Materials?, Zeitschrift des Vereins deutscher Ingenieure, 44, 1524–1530, 1900.

Nötzli, J., Gruber, S., and von Poschinger, A.: Modellierung und Messung von Permafrosttemperaturen im Gipfelgrat der Zugspitze, Deutschland, Geographica Helvetica, 65, 113–123, https://doi.org/10.5194/gh-65-113-2010, https://www.geogr-helv.net/65/113/2010/, 2010.

Phillips, M., Haberkorn, A., and Rhyner, H.: Snowpack characteristics on steep frozen rock slopes, Cold Regions Science and Technology, 141, 54 – 65, https://doi.org/10.1016/j.coldregions.2017.05.010, 2017.

Ravanel, L., Magnin, F., and Deline, P.: Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif, Science of The Total Environment, 609, 132 – 143, https://doi.org/10.1016/j.scitotenv.2017.07.055, 2017.

Renshaw, C. E. and Schulson, E. M.: Universal behaviour in compressive failure of brittle materials, Nature, 412, 897–900, https://doi.org/10.1038/35091045, 2001.

Shea, W. T. and Kronenberg, A. K.: Strength and anisotropy of foliated rocks with varied mica contents, Journal of Structural Geology, 15, 1097 – 1121, https://doi.org/10.1016/0191-8141(93)90158-7, http://www.sciencedirect.com/science/article/pii/0191814193901587, 1993.

Walter, F., Amann, F., Kos, A., Kenner, R., Phillips, M., de Preux, A., Huss, M., Tognacca, C., Clinton, J., Diehl, T., and Bonanomi, Y.: Direct observations of a three million cubic meter rock-slope collapse with almost immediate initiation of ensuing debris flows, Geomorphology, 351, 106 933, https://doi.org/https://doi.org/10.1016/j.geomorph.2019.106933, http://www.sciencedirect.com/science/article/pii/S0169555X19304246, 2020.

Weber, S., Faillettaz, J., Meyer, M., Beutel, J., and Vieli, A.: Acoustic and micro-seismic characterization in steep bedrock permafrost on Matterhorn (CH), Journal of Geophysical Research: Earth Surface, 123, 1363–1385, https://doi.org/10.1029/2018JF004615, 2018.