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Three- and four-point bending tests on artificial frozen soil samples at temperatures close to 0 °C

Yuko Yamamoto *, Sarah M. Springman

Institute for Geotechnical Engineering, ETH Zurich, Stefano Franscini Platz 5, 8093 Zurich, Switzerland

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ABSTRACT

Degradation of alpine permafrost under global climate change has led to accelerated downslope creep, volume loss due to thawing and surface fissures in rock glaciers. This may lead to mass movements evolving through instabilities. It is hypothesised in this paper that the formation of cracks in the frozen body of a rock glacier can lead to triggering of such failures, and that analogue instrumented beam bending tests (with 3 and 4 supports/loading points) can be used to investigate fracture mechanics in frozen soil, with applications derivable for rock glaciers. Likely transitions between unpredictable brittle behaviour (through rapid crack formation, propagation or matrix destruction) and a more ductile response (dominated by micro-crack nucleation), can be established and quantified as a function of acoustic emission activity, deformation rate, solids-ice content and specimen temperature between −3.2 °C and −0.5 °C.

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1. Introduction

Rock glaciers (Fig. 1a) are special geomorphic landforms in alpine periglacial environments and characterised by time-dependent, gravity-induced downslope deformation (Barsch, 1992). Typically, deformation occurs within an inhomogeneous ice-soil matrix (Fig. 1b) through secondary creep, while exhibiting temperature-dependent strain rate and ductile behaviour in enhanced shear zones within the rock glacier's core (e.g. Wagner, 1992; Arenson et al., 2002). However, complex thermal conditions, especially due to gradual warming in thermal degradation zones (Fig. 1c), may lead to significant changes in mechanical behaviour (Arenson, 2002; Vonder Mühll, 2003; Arenson et al., 2010; Haeberli et al., 2010; Springman et al., 2011; Springman et al., 2012; Buchli et al., 2013). Deformation of some rock glaciers has accelerated over past decades to several m/year and depressions and fissures are forming on the surface (Delaloye et al., 2008; Roer et al., 2008; Buchli et al., 2013, 2015), which are both parallel and perpendicular to the downslope movement (Kääb et al., 1998; Burger et al., 1999). Potentially, this accelerated, ongoing degradation could be aided by rapid fracture in the permafrost, such as was observed on the Graben Gufer rock glacier in 2009/2010, when surface movements reached 100 m/year (Delaloye et al., 2010).

Fracture is a significant process when dealing with fine-grained or frozen soils, since rapid crack formation and propagation may damage the soil matrix. This may cause sudden loss of strength (Thusyanthan et al., 2007; Azmatch et al., 2011). Transitions between unpredictable brittle behaviour (through rapid crack formation, propagation or matrix destruction) and a more ductile response (dominated by micro-crack nucleation), are dependent, primarily, on solid-ice-unfrozen water content, strain rate and temperature (e.g. Schulson and Duval, 2009; Akagawa and Nishisato, 2009). Furthermore, fissures provide a macro-flow-path for water, leading to progressive erosion in fine-grained soils (Harison et al., 1994). Infiltration of precipitation or snowmelt through fissures can affect the hydrological processes in rock glaciers (Buchli et al., 2013; Zhou et al., 2015), causing saturation and rapid increase of pore-water pressure in previously unsaturated soil. This could trigger slope instability (e.g. Fig. 1c).

It is hypothesised that crack formation in the frozen body of a rock glacier can lead to changes in behaviour and potential for initiation of landslides and debris flows. Fracture mechanics, and particularly transitions in brittle-ductile response in artificially frozen soil samples analogous to permafrost between −3.2 °C to −0.5 °C, has been investigated and quantified through beam bending tests (with 3 and 4 supports/loading points). The frozen soil specimens were instrumented to detect acoustic emissions to capture the progress of crack propagation during the tests.

2. Tensile and fracture toughness of frozen soil

The components of frozen soil strongly affect its response to thermo-hydro-mechanical loading, particularly in terms of the relationships between solids-ice-air-unfrozen water content and the free energy of soil water, suctions and pore pressures (Williams, 1964a, 1964b, 1966; Dash

* Corresponding author at: Dr. Vollenweider AG, Badenerstrasse 621, 8048 Zürich, Switzerland.
E-mail addresses: yamamoto@drvollenweiderag.ch (Y. Yamamoto), sarah.springman@igt.baug.ethz.ch (S.M. Springman).

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Notation

a	is the notched crack length of rectangular frozen soil sample [mm]
B	is the thickness of rectangular frozen soil sample [mm]
d_{max}	is the maximal grain size [mm]
L	is the length of the rectangular frozen soil sample [mm]
K_{Ic}	is the fracture toughness [kPa/$m^{0.5}$]
P	is the applied load [kN]
PIV	is the Particle Image Velocimetry
R^2	is the coefficient of correlation
T	is the temperature [°C]
w_i	is the volumetric ice content [%]
W	is the width of rectangular frozen soil sample [mm]
σ_f	is the flexural stress [kPa]
σ_{YS}	is the 0.2% offset yield strength in tension [kPa]

et al., 1995). Significantly less experimental research has been conducted on tensile extension tests in comparison with many research projects carried out to quantify compressive strength (e.g. Fish, 1985; Andersland and Ladanyi, 1994; Andersen et al., 1995; Arenson and Springman, 2005).

Tensile strength test methods can be divided into direct (tension test, many specimen forms) and indirect methods (split cylinder, four-point bending, Brazilian tests) (Azmatch et al., 2010). Three main variables affect the response: deformation rate, temperature and unfrozen water content.

Prior research (Table 1) was mainly conducted on poorly graded silts, which exhibit a steep decrease in tensile strength at temperatures close to 0 °C (Haynes, 1978). Unlike the well-graded soils studied here (Fig. 2), tensile strength is mobilised in silts at close to 0 °C due to suctions developing in the ice-soil-unfrozen water – air void matrix (Haynes, 1978; Akagawa and Nishisato, 2009; Christ and Kim, 2009; Azmatch et al., 2010, 2011). An increase of unfrozen water content as temperatures approach 0 °C results in a loss in suction and an associated decrease of tensile strength.

Akagawa and Nishisato (2009) investigated the tensile strength of a frozen fringe in Dotan silt within a relatively warm temperature range -0.15 °C > T > -1.31 °C. Frozen Dotan silt is 20–70 times stronger in tension than in its unfrozen state (164 kPa, $T = -1.31$ °C; $T = +0.6$ °C, 7.2 kPa). Azmatch et al. (2010) reported a ratio of 118 for Devon silt (827 kPa, $T = -0.65$ °C; 7 kPa, $T = 2.25$ °C).

Yuanlin and Carbee (1987) conducted uniaxial direct tension tests on saturated Fairbanks silts at temperatures between -1 °C > T > -10 °C and report that strain rate affected the failure mode more than temperature. The stress-strain behaviour for frozen soils is similar to that of ice (Arenson et al., 2007), showing ductile behaviour when experiencing lower-rate deformations, and brittle behaviour when experiencing higher-rate deformations (Schulson et al., 1984). Akagawa and Nishisato (2009) reported that the fracture mode changes from ductile to brittle with decreasing temperature, even

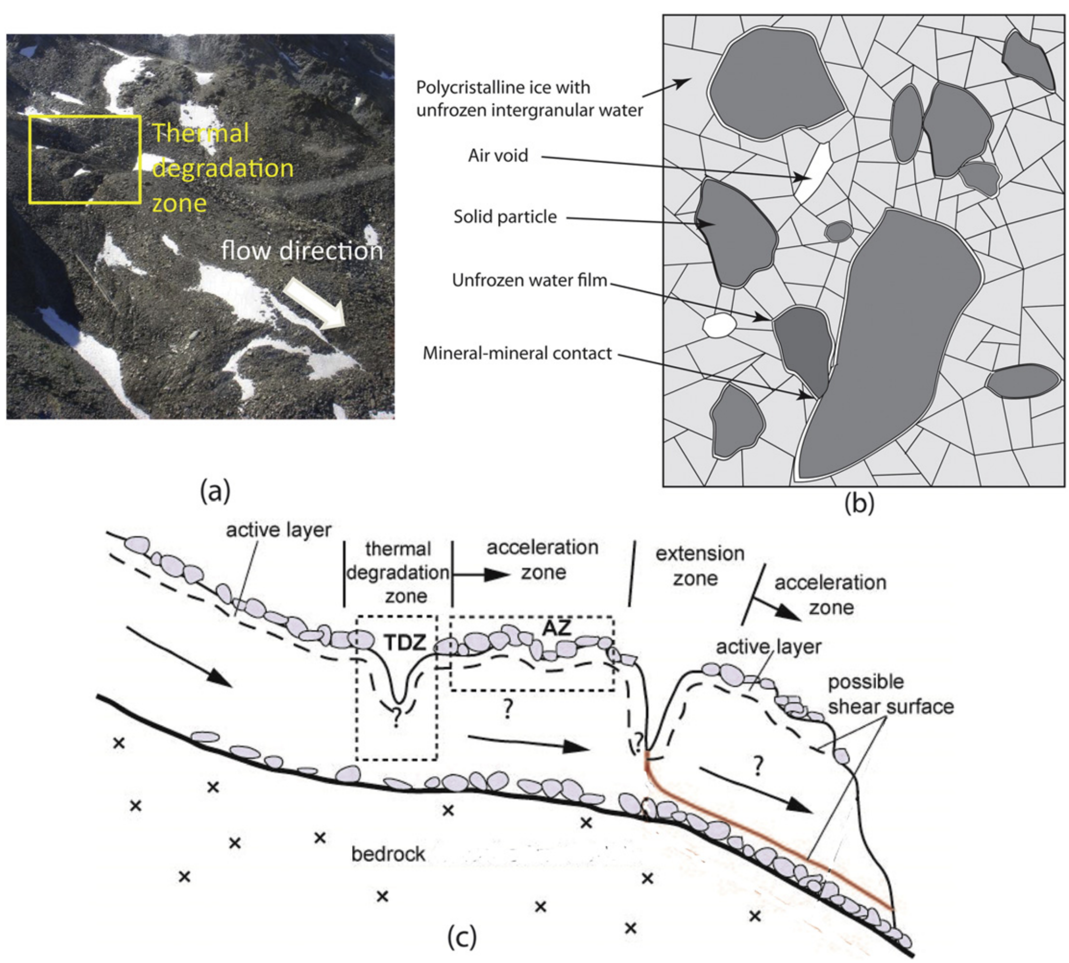

Fig. 1. a) aerial view of the Furggwanghorn rock glacier, Turtmanntal, Valais, Switzerland, (Photograph, Sarah Springman), b) Two-dimensional schematic of the structure of frozen soils (after Ting et al., 1983), c) Schematic cross section through a degrading rock glacier (after Springman et al., 2011).

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