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Rock glaciers, fault gouge and asphalt Hard particles in a nonlinear creeping matrix

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Abstract

Composite materials that are composed of hard particles within a soft matrix demonstrate two significantly different deformation behaviours. There is a threshold at which the particle interaction of the hard particles becomes the dominating process. For a low volumetric content of the hard particles, the strain rate of the composite is equal to the strain rate of the soft material reduced by a factor that is a linear function of the volume fraction of the hard particles f. The factor is thought to be material dependent. A value of $1-(5/3)f$ was found for the frozen soil under investigation. At large solids fractions creep deformatins are mostly eliminated by dilatancy. Due to the limited tensile strength of the pore ice, the large strain strength of the composite only depends on the strength of the unfrozen soil.

Keywords: Creep; Soil strength; Rock glacier; Frozen ground

1. Introduction

Rock glaciers are apparent geomorphological features of a permafrost environment. They occur in many mountainous regions, such as high in the Swiss Alps, and are complex inhomogeneous mixtures of ice with varying proportions of rock fragments (Giardino et al., 1987; Martin and Whalley, 1987; Barsch, 1996). Even though only a limited number of published data on the internal structure of rock glaciers is available (Whalley et al., 1994; Elconin and La Chapelle, 1997; Berthling et al., 1998; Arenson et al., 2002) a large spatial and temporal variations of the compositions can be noticed. Some rock glaciers show upper layers that may consist almost of pure ice, and the lower layers of mostly rock. Variations in temperature with time and depth further complicate the system *rock glacier*. The active layer at the top may experience temperatures well below freezing during the winter and well above zero centigrade during warm summers. The seasonal

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variations diminish with depth and are no longer recordable at a depth of about 15 m, depending on various factors, such as the location (e.g. Vonder Mühll and Haeberli, 1990). The mean annual temperatures get warmer with increasing depth. The base of the rock glacier does not have to be identical with the permafrost basis and temperatures above freezing may occur within this lower, generally blocky layer. This phenomenon might be typical for very old rock glaciers that experienced colder temperatures and where the permafrost base is slowly moving upwards (Vonder Mühll et al., 2003). In addition to the two constituents mentioned, air pockets form a third place, and there may be a fourth phase of unfrozen water. This can be present as flowing water in unfrozen channels or as adsorbed water around fine particles. In particular at temperatures close to the melting point of ice, the amount of unfrozen water can be very significant (Williams, 1967; Anderson and Tice, 1972). The engineering importance of rock glaciers rests on their possible involvement in natural hazard formation (after Strozzi et al., 2004):

- rockfall caused by continuous debris transport of active rock glaciers;
- potential source of debris flow due to steady mass transport by creep (Hoelzle et al., 1998; Kääb, 2000);
- triggering catastrophic slides due to reduction in strength as the ice gets warmer possibly provoked by climate change (Haeberli, 1992; Zimmermann and Haeberli, 1992; Haeberli et al., 1993, 1997; Davies et al., 2001).

The mechanical behaviour of ice is reasonably well understood and is dominated by creep at low deformation rates and by fracture at high rates (e.g. Palmer et al., 1983; Sanderson, 1988; Cole, 2001; Schulson, 2001). Assemblages of rock fragments are equally understood and are characterised by friction and dilation familiar in soil mechanics (Bolton, 1986). Active rock glaciers are a mixture of mainly ice and rock fragment, and if the mechanics are to be understood we need tractable constitutive models that idealise the leading properties.

At low solid particle (rock) concentrations, the mixture behaves as 'dirty' ice (e.g. Hooke et al., 1972). The rock fragments do not contact each other, but they hinder creep because they act as essentially undeformable inclusions. However, a small concentration of solid particles may result in smaller ice crystals and tests showed that the creep rates are slightly higher than those observed for pure ice (Weaver and Morgenstern, 1981). At higher rock concentrations, the fragments come into contact, and deformation then requires relative sliding and rotation between the fragments, accompanied by deformation of the ice in the pore spaces. Using data presented by Gougnour and Andersland (1968), Ting et al. (1983) proposed a failure mechanism map, which shows that various mechanisms are at play simultaneously, depending on the volume fraction of the Ottawa sand under investigation. At a temperature of -7 °C a significant increase in the peak strength was noted for volumetric ice contents below about 40%, where structural hindrance due to particle interaction plays a decisive role. Similar observation are reported more recently in Yasufuku et al. (2003) for direct shear tests on sand, and in Arenson and Springman (2005a) or Arenson et al. (2004) for triaxial shear test.

A comparable material occurs in earthquake faults, where in general a finite layer of damaged rock can be found rather than a sharp planar contact between walls of intact rock (e.g. Sammis et al., 1987; Ben-Zion and Sammis, 2003; Storti et al., 2003). Rock particles are fragmented, ground and compacted during the development of the fault to a heterogeneous material called fault gouge or fault breccia, where larger grains are included in a matrix of fine-grained powder or clayey material (e.g. Scholz, 1990). A distinction is usually made between granular gouges and clay gouges (Vrolijk and van der Pluijm, 1999). The latter types are of interest here, since the matrix seems to be of viscous nature that explain creep observation in such gouges (e.g. Thompson et al., 1997).

Another material of this type is paving asphalt, which is composed of rock fragments in a continuous matrix of a binder, blended at temperatures between 135 and 163 °C (Dongré et al., 1996; Read and Whiteoak, 2003). Bitumen, the most popular asphalt binder, is a highly viscous residue of crude oil, obtained by removing most of its volatile components (Hunter, 2000; Read and Whiteoak, 2003). A number of studies have demonstrated the effect of all kinds of particles on the viscosity and the elastic properties of