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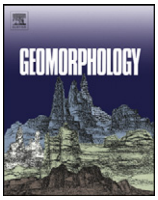

Biologically-initiated rock crust on sandstone: Mechanical and hydraulic properties and resistance to erosion

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ABSTRACT

Biocolonization on sandstone surfaces is known to play an important role in rock disintegration, yet it sometimes also aids in the protection of the underlying materials from rapid erosion. There have been few studies comparing the mechanical and/or hydraulic properties of the BIRC (Biologically-Initiated Rock Crust) with its subsurface. As a result, the overall effects of the BIRC are not yet well understood. The objective of the present study was to briefly characterize the BIRC from both the mineralogical and biological points of view, and especially to quantify the effect of the BIRC upon the mechanical and hydraulic properties of friable sandstone. The mineralogical investigation of a well-developed BIRC showed that its surface is enriched in kaolinite and clay- to silt-sized quartz particles. Total organic carbon increases with the age of the BIRC. Based on DNA sequencing and microscopy, the BIRC is formed by various fungi, including components of lichens and green algae. Using the method of drilling resistance, by measuring tensile strength, and based on water jet testing, it was determined that a BIRC is up to 12 times less erodible and has 3–35 times higher tensile strength than the subsurface friable sandstone. Saturated hydraulic conductivity of the studied BIRC is 15–300 times lower than the subsurface, and was measured to also decrease in capillary water absorption (2–33 times). Water-vapor diffusion is not significantly influenced by the presence of the BIRC. The BIRC thus forms a hardened surface which protects the underlying material from rain and flowing water erosion, and considerably modifies the sandstone's hydraulic properties. Exposing the material to calcination (550 °C), and experiments with the enzyme zymolyase indicated that a major contribution to the surface hardening is provided by organic matter. In firmer sandstones, the BIRC may still considerably decrease the rate of weathering, as it is capable of providing cohesion to strongly weathered (and disintegrated) sandstone surfaces. However, only a near-surface zone of the sandstone is stabilized by the BIRC, and additional sources of stabilization (gravity-induced stress, inorganic cement, etc.) contribute to the resistance of the subsurface zone of sandstone exposures.

1. Introduction

Due to its complexity and contact with the atmosphere, a sandstone surface is a critical zone, with properties affecting the erosion rate. Along with abiotic weathering and erosion factors, biotic factors are considered to play an important role both in the deterioration and stabilization of sandstone surfaces (Gorbushina, 2007 and references therein). Biocolonization on sandstone surfaces is known to play an important role in rock disintegration, yet it sometimes also aids in the protection of the underlying materials from rapid erosion. Our study is concerned with the effect of biologically-initiated rock crust on the mechanical and hydraulic properties of friable sandstone and its resistance to erosion.

1.1. Biocolonization of sandstone surfaces

Various types of organisms and their communities can be found on rock surfaces (epilithic) as well as within their subsurface (endolithic) (Golubic et al., 1981; Hirsch et al., 1995; Hallmann et al., 2013).

Different terms are used for these organisms and/or for the whole biologically-affected surface zone of sandstone, based on the range of the biological impacts, species, kinds of growth, or other characteristics; and are also based on the scientific field. The most common terms biofilm,

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Abbreviations: BSE, backscattered electrons; BIRC, biologically-initiated rock crust; B-surface, uneven non-tectonic surface with a developed BIRC; C-surface, exposed surface of a tectonic fracture with a developed BIRC; EPS, extracellular polymeric substances; F-surface, surface of tectonic fracture without a BIRC; K, hydraulic conductivity; PBS, phosphate buffered saline; REI, relative erodibility indicator; SEM, scanning electron microscope; TOC, total organic carbon; TS, tensile strength; TSP, tensile strength parallel with the surface; TSP_{dry}, tensile strength parallel with the surface done on dried prisms; TSP_{wet}, tensile strength parallel with the surface done on wet prisms; Tx, capillary water absorption rate; δ, diffusion coefficient.

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bio-coating, biotic crust, biocrust, or simply crust are used for the complex communities of organisms living on the rock surface and/or penetrating it to depth (for references and details see Supplementary material). This paper deals specifically with the young biologically-inhabited and hardened sandstone surface and near subsurface zone of the rock including both the epilithic and endolithic microorganisms. Therefore, in this paper we used the term "biologically-initiated rock crust" – BIRC.

In general, the biologically-affected surface zone of sandstone reaches to several millimeters in depth (Gómez-Alarcón et al., 1995; Chen et al., 2000; Lisci et al., 2003). Due to their modular and adaptable growth, fungi dominate in the BIRC, and fungal hyphae may constitute >90% of the biomass volume (Bjelland and Thorseth, 2002; Gorbushina, 2007). Other common organisms are cyanobacteria, algae and bacteria (Ahmadjian, 1993; Hirsch et al., 1995). Development of microcolonies embedded in extracellular polymeric substances (EPS) is responsible for binding cells and other particulate matter together and to the substratum (Warscheid and Braams, 2000). A moist, sticky surface provided by the EPS may promote the trapping of airborne clay (Dade et al., 1990).

1.2. Role of microorganisms in erosion and protection

A great number of studies have been focused on the effects of microorganisms on rock surfaces (Gorbushina, 2007). Several studies demonstrated clear evidence of biodeterioration/bioweathering (e.g., Friedmann, 1982; Paradise, 1997; Robinson and Williams, 2000). Mechanical damage mainly proceeds due to penetration of the substrate by hyphae, as well as the expansion and contraction of lichen thalli due to changes in moisture content (Wessels et al., 1995; Lisci et al., 2003). Biochemical weathering is mediated by both organic and inorganic acids as well as metal-complexing compounds (Bjelland and Thorseth, 2002). Fungi were found to play a considerable role in stone weathering, either as part of the lichen mycobiont (Smits et al., 2009; Cutler et al., 2013) or as free-living form (Chen et al., 2000). Cyanobacteria are clearly capable of dissolving quartz due to an increase in pH to 11 in the vicinity of photosynthesizing cells (Büdel et al., 2004; Brehm et al., 2005). Conversely, other studies have reported that the BIRC-related phenomenon is also capable of protecting sandstone surfaces from wind abrasion, raindrop impact, water flow, temperature variations, and deposition of salts; therefore, it can possibly decrease the erosion rate (Gómez-Alarcón et al., 1995; Grondona et al., 1997; Souza-Egipsy et al., 2004; Viles and Goudie, 2004). The protective role of a biotic crust is widely documented on soils in arid and semiarid landscapes, where they stabilize various friable surfaces, and also positively influence the hydrology and other parameters (e.g., Warren, 1995; Kidron, 1999; Langhans et al., 2009; Pointing and Belnap, 2012).

Among other parameters, the moisture content, saturated hydraulic conductivity (K), vapor permeability, and capillary water absorption were measured to characterize the decrease of permeability of the pore space caused by the presence of BIRC (cf., Dennis and Turner, 1998; Thullner et al., 2002; Seifert and Engesgaard, 2012). It is important input data as water transport and moisture affect many weathering processes (Mol and Viles, 2013; Paradise, 2002). It was found that the BIRC modifies the capillary water uptake, causing measurable alterations in water-vapor diffusion, and surface-active compounds of biotic origin protect the microorganisms against water loss and desiccation (Warscheid and Braams, 2000).

The protecting effect of BIRC is commonly inferred from comparisons of lichen-inhabited and lichen-free surfaces (e.g., Arino et al., 1995; Mikuláš, 1999). However, most of above-mentioned studies neglect the possibility that biota may, in fact, already colonize relatively stable surfaces, and thus their presence might be the consequence, not the cause of the surface stability. Only a few studies have directly proven the stabilizing effect of the biotic crust (Kurtz and Netoff, 2001).

To our knowledge, there have been no studies published dealing with the quantification of both the mechanical and hydraulic properties (i.e., the parameters critical for weathering) of BIRC sandstone surfaces and their deeper subsurface zone. We believe that such information may disclose the role of biocolonization (i.e., formation of the BIRC) in the erosional response of weak sandstone exposures.

1.3. Objectives

The major objective of this study was to determine how the BIRC changes the mechanical and hydraulic properties of a weak sandstone surface, and how it influences resistance to erosion. The following partial tasks were resolved in order to fulfill this objective:

1) A brief characterization of the BIRC from both the mineralogical and biological points of view to determine whether the mechanical properties of BIRC are caused by organic or inorganic matter.
2) Determination and evaluation of the properties measured on the BIRC, in the deeper subsurface below the BIRC (i.e., in the original sandstone), and also on the bare surface.
3) A comparison of the properties of the initial and matured BIRC in order to elucidate the rate of colonization and hardening of the sandstone surface.
4) Determination if the BIRC is sufficient to protect the sandstone surface or if other factors are involved in the hardening of young weak sandstone surfaces.

In addition, we examined the effect of gravity-induced stress (i.e., internal rock pressure caused by gravity loading) onto a studied sandstone surface, since it has recently been found that increased gravity-induced stress strongly decreases the weathering and erosion rate of friable sandstone (Bruthans et al., 2014).

To achieve the above listed tasks, the study was focused on the BIRC and bare surfaces of a friable sandstone in a quarry, which had several benefits: (i) the surfaces are young (years to decades), so the effect of long lasting processes (like mineral case hardening) is unlikely; (ii) the contrast in properties of the BIRC and the deeper subsurface zone (i.e., inner friable and permeable sandstone) could be significant; and (iii) commonly used destructive techniques could be applied here.

2. Study site and sandstone characterization

The study area was the active Střeleč Quarry situated close to the Bohemian Paradise Protected Landscape Area in the Czech Republic (Fig. 1; Bruthans et al., 2012). The whole area is formed by the Hrubá Skála Sandstone formation and it is known due to attractive "rock cities" with numerous pinnacles up to 60 m high, as well as overhangs, arches and other landforms (Adamovič et al., 2006). Mean annual precipitation in the area is 790 mm (Holenice 2005–2014, Czech Hydrometeorological Institute).

Fine to medium grained quartz sandstone, with a planar stratification (4–18° to south-southwest), is interpreted as a coarse-grained delta body deposited in a shallow marine environment during the Turonian, Cretaceous (Uličný, 2001).

The study was focused on the so-called glass industry sandstone, which is white if freshly exposed on quarry faces, and yellowish to light green/gray if covered by a BIRC. Its matrix consists of kaolinite, quartz silt, and minor illite. Kaolinite is the primary cementing agent for the quartz grains, although contact diagenetic silica cement has developed locally (Hauser et al., 1965). The mean sandstone density is 2.0 g/cm^3, the porosity is 22%, the clay fraction content is 1.4%, and K is 5.10^{-5} m/s.

The sandstone studied is more friable than common cemented sandstones in the Bohemian Cretaceous Basin; the firmest portions of the sandstone have a mean uniaxial compressive strength of 14 MPa and a tensile strength of 280 kPa (Bruthans et al., 2012). On the other hand, some zones of the sandstone in the quarry are