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Evolution of fracture normal stiffness due to pressure dissolution and precipitation

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ABSTRACT

The normal stiffness of a fracture is a key parameter that controls, for example, rock mass deformability, the change in hydraulic transmissivity due to stress changes, and the speed and attenuation of seismic waves that travel across the fracture. Non-linearity of normal stiffness as a function of stress is often attributed to plastic yield at discrete contacts. Similar surface-altering mechanisms occur due to pressure solution and precipitation over larger timescales. These processes partition the fracture surfaces into a flattened contact region, and a rough free surface that bounds the void space. Under low loads, contact occurs exclusively over the flattened part, leading to rapid, exponential stiffening. At higher loads, contact occurs over the rough surface fraction, leading to the conventional linear increase of stiffness with stress. It follows that a relationship exists between the history of in situ temperature and stress state of a rock fracture, and its subsequent deformation behavior.

1. Introduction

Fractures are widespread in the Earth's crust and often control the overall behavior of rock masses at large scales. Heat and mass transport, fluid flow, and the velocity and attenuation of seismic waves are all generally stress-dependent in fractured rock. Normal stiffness is a key parameter that relates relevant fracture properties to the magnitude of the normal stress. As such, it represents the stiffness contribution attributable to the closure of the void space between the rock walls, and the excess compression of contacting asperities therein with respect to the intact rock[17]. The fracture normal stiffness is the main factor that controls the P-wave transmission and reflection coefficients[66], and is closely correlated to the hydraulic transmissivity[65].

The numerical value of the normal stiffness will strongly depend on the morphological properties of the fracture, such as roughness and the correlation between the surfaces in contact, and the elastic moduli of the rock[31,65,89]. Chemically-mediated processes may significantly alter fracture morphology, thereby changing the hydro-mechanical properties of a rock fracture after formation[16,39,44,62,84]. These processes occur either as diagenetic mechanisms over geologic timescales at in situ conditions, or during engineering procedures, where injected fluids and induced temperature changes can accelerate these processes significantly. In open fractures, where opposing surfaces are not in nominal contact, the process of precipitation dominates, to structurally seal the discontinuity over time[38]. The formation of bridging structures precedes this sealing[36], and these structures control the deformation behavior of the fractures[73]. Large fractures that form highly connected networks are expected to be under compression at appreciable depth[6,90]. The relative displacement between the opposing rough rock surfaces, and the resulting partial contact, give rise to their effect on fluid flow, transport and displacement[10,88,89]. For these fractures, the coupled processes of pressure solution and free-face precipitation constitute significant diagenetic mechanisms[24,27,53]. Their combined effect leads to a redistribution of material, driven by spatial gradients in chemical potential, from the mechanically stressed grain contacts to the mechanically open pore space[28,41,69,81]. Although the hydraulic response to such compaction processes on fractures have been extensively studied[19,44,45,62,84], quantitative studies of the mechanical effects are sparse, and they remain experimentally challenging.

Building on previous work[37], the present study presents coupled hydro-mechanical-chemical simulations at the pore scale to assess changes in fracture normal stiffness under the effects of pressure solution and precipitation, for a water-quartz system. Specifically, instantaneous fracture closure curves are generated, for specific points in time during the dissolution and precipitation process, and related to changes in the rock surface morphology (Fig. 1). For a fracture undergoing pressure dissolution, the area of

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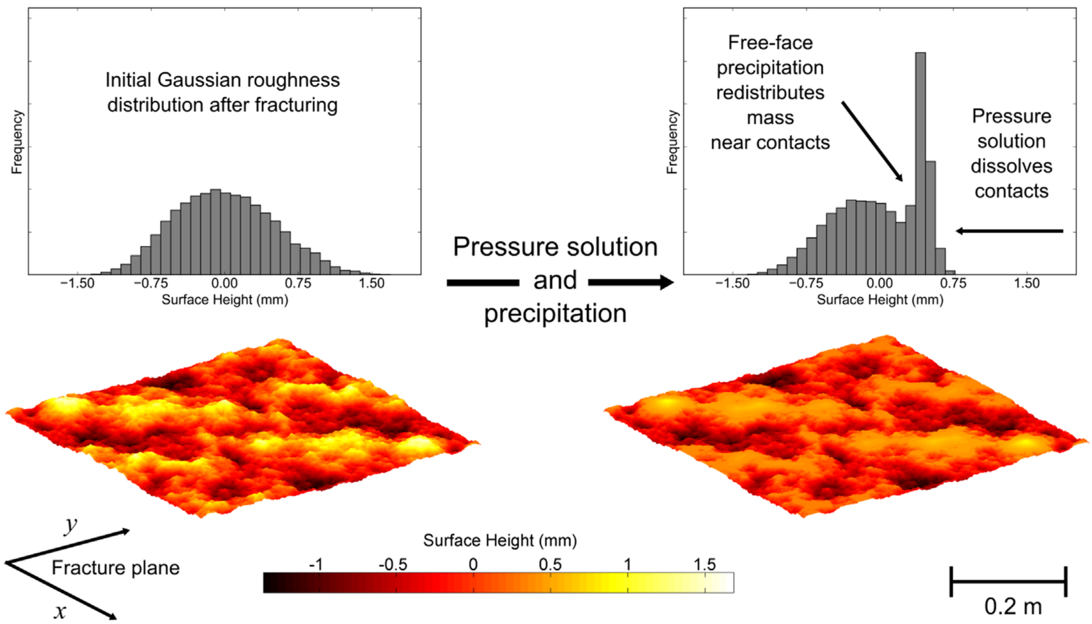

Fig. 1. A 0.5 × 0.5 m periodic fracture composite surface in its initial state (left) and after pressure solution and free-face precipitation acted for 300 ka at 10 MPa effective confining pressure and 150 °C (right).

discrete contact between the two rough surfaces increases, the number of contact patches that make up this discrete contact area increases, and the dominating contact regime changes from dissolved, smoothened contacts to unchanged, rough contacts. The ensuing changes in fracture closure behavior are in qualitative and quantitative agreement with experimentally obtained curves for multiple compression cycles on unmated fractures, where plastic damage leads to similar alterations of the rock surface morphology.

2. Methodology

The normal stiffness of a fracture is largely attributable to the frictionless contact between two rough surfaces. This contact problem is equivalent to the contact between a flat, elastic body with composite moduli, and a rigid body with a composite profile[12]. The profile of the composite surface is obtained as the sum of the opposing surface heights, and thus represents the aperture profile at unstressed conditions, i.e., when the two rough surfaces touch at a single point. A fracturing process produces two surfaces of isotropic, self-affine nature of approximately Gaussian height distribution[12,63,74]. The roughness power spectrum $C(q)$ sufficiently characterizes both the root-mean-squared roughness, and the height correlation of such surfaces as[49]:

$$C(q) = \frac{1}{(2\pi)^2}\int \langle h(\boldsymbol{x})h(\boldsymbol{o})\rangle e^{-i\boldsymbol{q}\cdot\boldsymbol{x}} d^2x \tag{1}$$

where$\boldsymbol{q}$ is the roughness wave vector, and $q = |\boldsymbol{q}|$ is its magnitude, the wavenumber, or spatial frequency. For measured data of $h(\boldsymbol{x})$, which are usually shifted to obtain $\langle h \rangle = 0$, Eq. (1) can be evaluated using a *Discrete Fourier Transform* and radial averaging. A numerical algorithm[59], has been implemented for this purpose. An ideal spectrum $C(q)$ for surfaces of this kind is given by (e.g[52].)

$$C(q) \propto \begin{cases} 1 & q_L < q < q_0 \\ q^{-2(H+1)} & q_0 \le q \le q_1 \\ 0 & q_1 < q < q_\ell \end{cases} \tag{2}$$

In Eq. (2), $q_L = 2\pi/L$ is the smallest roughness frequency that can possibly occur in the surface, limited by the sample length L. This wavenumber q_L corresponds to the largest possible roughness wavelength $\lambda_L = L/2\pi$ occurring in the surface. At the other end of the spectrum, the largest possible roughness frequency, q_ℓ, or smallest roughness wavelength, is limited by the lattice size ℓ. Note that q_L, or λ_L, is a consequence of the physical size of the surface of interest, and q_ℓ is a consequence of discretization. The discretization limit may result from a numerical lattice or grid size, or may result from limitations in measurement resolution. For example, a surface of length L has a cell size of $\ell = L/\mathcal{L}$, where $\mathcal{L}$ is the number of equally sized square lattices. Surfaces in nature have no notion of a discretization-induced limit λ_ℓ, but are rough down to the molecular scale[42,82]. A surface with roughness wavelengths bounded by its size and discretization limit is shown in Fig. 2a, and the associated power spectrum in Fig. 2a. Surfaces of this kind are good models of naturally induced tensile fracture surfaces[58], apart from having a lower limit, q_ℓ, that is an unavoidable numerical artifact. In between the limits (q_L, q_ℓ), two more characteristic wavelengths may exist .

If the smallest roughness wavelength present on a surface is larger than the discretization limit λ_ℓ, a so-called cut-off wavelength $\lambda_1 > \lambda_\ell$ exists, and a corresponding cut-off wavenumber $q_1 < q_\ell$; see Figs. 2c and d. As a consequence, surfaces with a cut-off lack smaller roughness features; compare Figs. 2a where $q_1 = q_\ell$ and 2c where $q_1 < q_\ell$. In this case, only larger roughness features are represented, i.e., the surface appears smoother for the lack of small-scale roughness. This is equivalent to a low-pass filter, in terms of roughness frequency. Although real surfaces don't feature such a cut-off, it has been shown that ignoring theses small roughness features has negligible effects when numerically computing normal stiffness[14] or transmissivity[50,79,87]. In other words, many phenomena in fractures depend mostly on the largest roughness wavelengths of the contacting surfaces. Introducing a cut-off wavelength is (1) unavoidable when representing a surface discretely, because at the most the discretization bound represents the artificial limit $q_1 = q_\ell$, and (2) a convenient means of obtaining first-order solutions with limited computational effort.

If the largest roughness wavelength present on a surface is less than the physical limit λ_L, a so-called roll-off wavelength $\lambda_0 < \lambda_L$