Frictional Behavior of the Stressed Basalt Fracture

Lei Wang\textsuperscript{1,2}, Zhen Zhong\textsuperscript{1,2*}, Yunjin Hu\textsuperscript{1,2}, Jianhang Ding\textsuperscript{1,2}

\textsuperscript{1}Key Laboratory of Rock Mechanics and Geohazards of Zhejiang Province, Shaoxing University, Shaoxing 312000, China
\textsuperscript{2}School of Civil Engineering, Shaoxing University, Shaoxing 312000, China

The corresponding author, Zhen Zhong, zhongzhen@zju.edu.cn, https://orcid.org/0000-0002-7116-8295

Abstract. The frictional properties and sliding stability of rocks are critically important in several fields, e.g., earthquake dynamics, extraction of underground resources, and sequestration of carbon dioxide. Here a self-developed triaxial apparatus was employed to conduct sliding tests under the coupled hydro-mechanical (HM) conditions. We determined the evolution of frictional strength in the stressed basalt fracture. The relations were established through velocity-stepping (VS) experiments on split basalt core subject to various stress, infill, and hydraulic conditions. The basalt exhibited velocity-strengthening behavior under cyclic velocities of 1–30 \( \mu \)m/s. Moreover, the frictional property was observed to be stress- and infill-dependent, showing lower frictions at both larger effective normal stresses and larger infill thickness. Besides, the sliding stability of the basalt fracture is found to be velocity- and stress-dependent. In particular, an unstable slip of a stick-slip was observed at a small velocity of 1 \( \mu \)m/s, but stabilizes with increasing shearing velocities at about 6 \( \mu \)m/s. Meanwhile, there is a transition from stable slip to unstable slip with the increasing effective normal stress, which is 5 MPa. Whereas, the thickness of the gouge as large as 2 mm does not seem to influence the sliding stability, even though the gouge thickness will significantly weaken the frictional strength of basalt fracture. The results suggested that the evolution of basalt fracture friction is controlled considerably by hydro-mechanical conditions, the sliding velocity, and gouge thickness. The frictional strength tends to vary with specified hydraulic, mechanical, gouge-bearing conditions. Furthermore, the frictional behavior transits between stable- and unstable-slip based on the velocities, stress pore pressure, and gouge thickness. These conclusions are drawn from constrained conditions.

1. Introduction
The mechanical strength and stability of rock mass are highly dependent on the rock discontinuities, including fractures and faults. Therefore, a good characterization of frictional properties and sliding behaviors of rock or existing faults is required for multiple applications such as the earthquake cycle [1–4], the sequestration of carbon dioxide [5–6], and enhanced geothermal stimulation [7–8].

Over the past several decades, substantial efforts have been made to explore the evolution of rock faults' mechanical properties under various loading and ambient conditions [9–11]. Specifically, on fault friction and sliding stability, wherein it was reported that the frictional strength of fault is rate- and state-dependent, which can be described by rate-and-state friction laws [1,12–14]. In addition, friction properties are affected by a variety of factors, including mineralogical compositions of rocks or faults [11,15], confining stress [16–18], gouge properties and thickness [19–21], pore fluid pressure [22–24], and temperature [25–28]. It has been shown that minerals that strengthen with increased slip velocity, such as most clay minerals, exhibit stable sliding [29–31], whereas those that weaken with increasing velocity, such as quartz, can undergo stick-slip sliding [32–33]. Moreover, the importance of fluids in fault zones is apparent [22], and fluids play mechanical (i.e., reduction of mean effective stress within faults induced by fluid overpressurization), and chemical (i.e., densification/lithification and cementation of fault gouge driven by chemical potential gradients) roles in faulting phenomena.
The mechanical and chemical effects are complexly related. Despite the known importance of these factors, the complex interplay of those factors on the frictional properties is poorly understood. This study develops an apparatus to explore the mechanical properties and sliding stability of split basalt cores. The split cores are sheared at cyclic sliding velocities of 1–30 μm/s under a range of effective normal stresses (1, 3, and 5 MPa). The evolution of friction is measured concurrently during the experiments. Moreover, the effects of gouge thickness and pore pressure on the frictional behaviors are analyzed.

2. Experimental Materials and methods
The tested basalt was extracted from basalt mesa in Xinchang, Zhejiang, China, a region identified as a wide-spread area with geohazards, such as landslides. The mineralogical composition of the samples was characterized via X-ray Diffraction. The basalt is fine-grained and consists of Augite (60%), Anorthite (34%), Clinoclore (6%) in volumetric fractions. Figure 1 demonstrates the preparation of the experimental sample. For the experiments, cores with longitudinal lengths of 5 cm and diameters of 2.5 cm are drilled from the rough sample. Next, the formed fracture surfaces are carefully saw cut and polished into two halves. Finally, the formed fracture surfaces are roughened to a repeatable roughness by using a 60 grit ceramic abrasive.

A triaxial apparatus was developed to conduct shear-flow coupling experiments. As illustrated in Figure 2, the apparatus consists of a core holder, four servo-controlled syringe pumps (ISCO 500D), and control & acquisition systems. The core holder is designed for direct-shear configuration and comprises four axial rods, which transmit axial stress (τ) to the split core. In this configuration, each rod, driven by the servo-controlled pump, is independent of advancing in the relative directions with a maximum stroke of 2 cm, facilitating the direct-shear of the split core. For the loading and flow systems, the syringe pumps exerted the confining pressure, axial load, and pore pressure with an accuracy of ± 0.007 MPa. Specifically, the axial stress is applied by pumps A and B at the constant load or displacement rate mode, the normal stress is applied by pump C, and the fluid flow is injected by pump D at a prescribed flow rate or pressure. Pressure or flow rate of the pumps are recorded via (National Instruments) LabVIEW DAQ system. Axial displacement under the applied shear stress is measured by a linear variable displacement transducer (LVDT) to ±1 μm, as a confirmation of the displacement rate applied by the pump and the measured axial stress (pump A and B). The reassembled split samples are packed within a rubber jacket, used to isolate the samples from the confining fluid. The jacketed samples are then axially loaded between the rods in the core holder.
### 3. Results and Discussions

Velocity-stepping (VS) experiments are conducted under various stress, infill, and hydraulic conditions to illuminate frictional strength and velocity dependence of split rock cores. The test conditions are summarized in Table 1. The cyclic velocities of $1 \rightarrow 6 \rightarrow 30 \rightarrow 6 \rightarrow 1 \mu m/s$ are used to test the reversibility of velocity dependence. For the gouge-bearing fractures, the crushed basalt powder is used to simulate fault gouge, and the size distribution of the basalt gouge is shown in Figure 3.

![Figure 3: The particle size distribution of gouge used to fill the fracture](image)

![Figure 4: Numerical calculation model of basalt fracture shear-seepage flow](image)
Table 1. Lists of experiments and related conditions: experiments were performed to evaluate fault strength and stability under a cyclic velocity ranging from 1 - 30 μm/s. We report experimental number (exp.), effective normal stress ($\sigma_n$), pore fluid pressure ($P_f$), initial infill gouge thickness ($d$).

| Exp. | Varying parameter | $\sigma_n$ (MPa) | $P_f$ (kPa) | $d$ (mm) | $V$ (μm/s) |
|------|------------------|------------------|-------------|----------|------------|
| s1   |                  | 1                |             |          |            |
| s2   | $\sigma_n$      | 3                | 0           | 0        |            |
| s3   |                  | 5                |             |          |            |
| s4   |                  |                  | 0           |          |            |
| s5   | $d$              | 3                | 0           | 0.5      | Cyclic velocity: 1–30 μm/s |
| s6   |                  |                  | 2           |          |            |
| s7   | $P_f$            | 1                | 0           |          |            |
| s8   |                  | 70               | 0           |          |            |
| s9   |                  | 150              | 0           |          |            |
| s10  |                  | 300              |             |          |            |

At the same time, the numerical simulation software UDEC was utilized to simulate the evolution of the frictional strength in the stress basalt fracture, where the established model is shown in Figure 4. The physical and mechanical parameters of the rock block are: a density of 3 g/cm³, an elastic modulus of 70 GPa, a cohesion of 35 MPa, an internal friction angle of 52°, a Poisson's ratio of 0.25, and a tensile strength of 4 MPa, while those of the joint parameters are: a normal stiffness of 250 GPa, a shear stiffness of 125 GPa, an internal friction angle of 22°, and cohesion of 0.1. The displacement of the upper and lower boundaries of the test block in the Y direction is constrained, and the normal stress $\sigma_n$ applied to the upper and lower surfaces is 1, 3, and 5 MPa, respectively.

Figure 5. The results of cyclic-velocity tests showing the evolution of frictional coefficient under various (a) effective normal stress, (b) infill thickness, (c) pore fluid pressure, and (d) comparison between experiment and numerical simulation.

Figure 5 shows the evolution of friction coefficient and velocity dependence of basalt fracture under cyclic velocities ranging from 1 to 30 μm/s. Frictional strength of basalt fractures is observed to be stress- and infill-dependent, where the fractures were weakened by the increasing normal stress and...
gouge thickness, showing lower frictions at both larger effective normal stresses and infill thickness. Moreover, as shown in Figure 5 (c), the friction of bare basalt fracture declines with increasing pore pressure, indicating the lubrication effect of pore fluid on the frictional strength. Figure 5 (a) also shows that unstable slip of stick-slip will appear at a small velocity of 1 μm/s, but later stabilize with increasing shearing velocities at about 6 μm/s. Meanwhile, there exists a transition from the stable creep slip to the unstable stick-slip with increasing effective normal stress, which is determined to be 5 MPa. The velocity dependence shows a positive relation between the friction and the shear velocities. The coefficient of friction increases as the velocities, indicating a stable slip under velocities ranging from 1–30 μm/s. Figure 5 (d) compares the results of numerical simulations under the same experimental conditions. Herein, the basalt fissures are prone to unstable sliding at low speeds, such that as the sliding speed increases, the sliding mode stabilizes. On the other hand, the friction strength is also positively correlated with the shear speed. These conclusions are consistent with the experimental results.

The velocity dependence of friction can be interpreted by the rate-and-state friction (RSF) theory [12–14]. In the RSF equation to model fracture shear slip, the friction coefficient is given by [12, 34–35]

\[
\mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_\sigma} \right)
\]

where, upon a velocity increase from \( V_0 \) to \( V \), the coefficient of friction (\( \mu \)) suddenly changes (direct effect, \( a \)) from a reference steady-state (\( \mu_0 \)) and then evolves to a new steady-state (evolutionary effect, \( b \)) over a characteristic critical slip distance (\( D_\sigma \)), \( \theta \) is the state variable.

The dependence of frictional strength on slip rate is described by the friction rate parameter (\( a-b \)). A positive value of (\( a-b \)) denotes velocity-strengthening behavior, suggesting stable, aseismic slip, while a negative (\( a-b \)) indicates velocity-weakening behavior, potentially unstable slip.

Figure 6 shows the friction rate parameter for a series of experiments with different initial thicknesses of basalt gouge and pore pressure. Overall, the basalt fracture shows velocity-strengthening behavior. Moreover, the friction rate parameter is observed to be stress-, fill-, and hydraulic- dependent. By increasing effective normal stresses, larger infill thickness, and pore pressure can potentially reduce the value of \( a-b \). However, this study did not observe velocity-dependent transitions as in other works [36], the limited experiment conditions may restrain this.

![Figure 6](image)

**Figure 6.** The effects of (a) gouge thickness and (b) pore pressure on the correlation between the friction rate parameter \( a-b \) and effective normal stress

4. Conclusions

Laboratory shearing experiments were performed on split basalt core subjected to various stresses, infills, and hydraulic conditions. From the results, the frictional strength of the basalt fractures is stress-, infill-, and hydraulic-dependent, where friction coefficient declines with an increment in effective normal stress, gouge thickness, and pore pressure, indicating the lubrication effect of gouge
and pore fluid on the frictional strength. In addition, the sliding stability of the fracture is also influenced by the normal stress and shear velocities. Specifically, the unstable slip of stick-slip appears at a small velocity of 1 μm/s, but stabilizes with increasing shearing velocities at about 6 μm/s. Meanwhile, there is a transition from stable creep slip to unstable stick-slip with increasing effective normal stress, which is 5 MPa. Moreover, the cyclic velocities tests show that frictional strength is velocity-dependent, and friction coefficient tends to increase as shear velocities, showing velocity-strengthening behavior. Thus, we conclude that the evolution of basalt fracture friction is significantly controlled by hydro-mechanical conditions, the sliding velocity, and gouge thickness. The frictional strength varies with the specified hydraulic, mechanical, infilled conditions. In addition, the frictional behavior transits between stable- and unstable- slips subjected to changing velocities, stresses, pore pressures, and gouge thicknesses. Nevertheless, it is essential to note that those conclusions are drawn from constrained conditions.

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