Micromechanics of Rock Friction
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Two manuscripts are completed and are in the process of review. The results are discussed in Synopsis 1 and 2 at the end of the report. We have observed a systematic roughness dependent evolution of friction in the first several hundred microns of displacement which are reported in Synopsis 1, and typical observations are presented in Fig. 1 and 2. An elastic contact model has successfully been applied to the initial stages of slip. Synopsis 2 shows that we can successfully model the shear stress-displacement relation in the earliest stages, the modeling being constrained by the topographic data. The initial slip model indicates that resistance to slip is provided by an asperity scale coefficient of friction of ~0.35 or an adhesive strength term of 5 GPa. Beyond this we note that the surfaces continue to strengthen to friction coefficients of ~0.50 to 0.65. This strengthening is due to slip hardening mechanism of ploughing and asperity interlock. Two projects to determine the nature of these mechanisms are currently in progress.

One project involves measuring the friction of different surfaces of quartzite and granite sliding on surfaces of optically flat sapphire. The greater hardness of the sapphire and its flatness prevent ploughing or asperity interlock from occurring. The friction measured must arise solely from shearing of contacts. We have successfully conducted friction test on sapphire samples to normal loads of 20 MPa with no damage to the sapphire. Typical friction coefficients are 0.15 to 0.18 independent of roughness. In Synopsis 2, two alternative asperity strength terms are discussed, one due to an asperity scale coefficient of friction and another due to an adhesion strength term. The sapphire experiments disagree with the adhesion model and agree with the simple friction model. They also indicate that only about half the asperity friction is due to shearing. We have now initiated a final series of experiments involving different roughnesses of sapphire and quartzite. The results of these experiments will allow us to determine the ploughing term for the surfaces which will then be used to study asperity interlock.

We have also planned a series of experiments to explore the mechanism of slip hardening. In Paper 1 (see Synopsis 1) it was shown that slip hardening correlates with normal closure of the surfaces. Increasing closure is coincident with slip hardening and it was shown that cessation of closure marks the onset of steady state friction. This is shown in Figure 1. To do this we have developed a technique to measure the evolution of contact during slip. Brown and Scholz, (1985) and Yoshioka and Scholz, (1989) have already shown than short, rapid, normal and shear pulses (glitches) can be used to test the normal and shear stiffness of the surface during sliding. We have built and tested an electronic control unit that will generate a preprogrammable sequence of normal and shear glitches and have begun testing it. The results can be summarized in Figure 2, a plot of the shear stiffness of the surface as a function of displacement. The figure shows that the shear stiffness increases with increasing displacement from ~2.4 MPa/micron following 60 microns slip to ~5 MPa/micron after 160 microns. We believe the increasing shear stiffness is due to increasing normal closure resulting from asperity interlock during slip hardening as shown in Figure 2. Once a complete set of values for shear stiffness vs. slip distance are collected, we will invert for the contact properties at various stages during slip hardening.

References

Brown, S. and C. H. Scholz, Closure of random elastic sufaces in contact, *J. Geophys. Res.*, *90*, 5531-5545, 1985.

Yoshioka, N., and C. H. Scholz, Elastic properties of contacting surfaces under normal and shear loads, *J. Geophys. Res.*, *97*, 17681-17700, 1989.

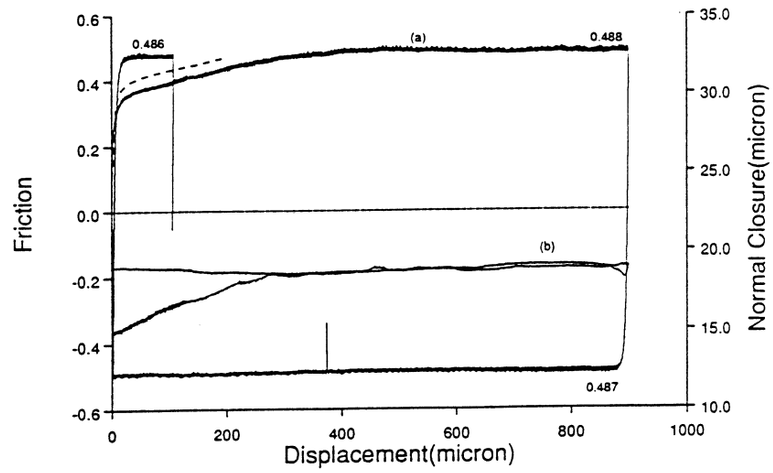

Figure 1. Friction-displacement diagram for granite, showing evolution to steady-state friction.

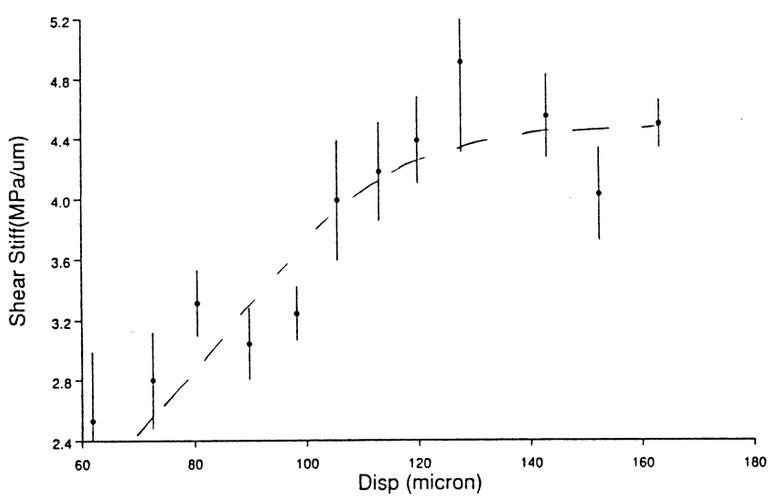

Figure 2. Shear stiffness-displacement plot showing evolution of shear stiffness with displacemnent due to asperity interlock during normal closure as shown in Figure 1.

Synopsis 1: Micromechanics of Friction in Rock:
1. Effects of Surface Roughness on Initial Friction and Slip Hardening in Westerly Granite

R. L. Biegel, W. Wang, C. H. Scholz, G. N. Boitnott, and N. Yoshioka

Friction was measured for sliding surfaces of Westerly granite sheared in a rotary apparatus at normal stresses up to 20 MPa. A profilometer measured the roughness before and after each experiment, and these data were used to paramaterize and classify the surface roughness. Axial displacement tranducers measured the normal closure. Total accumulated slip for most experiments was less than 200 microns, but several were extended to a few cms. We observed that macroscopic frictional properties evolved toward steady state through two distinct regimes. We call these transitional stages "initial slip" and "slip hardening." Finite shear compliance of the surfaces was observed the instant shear loading began and the shear stress was observed to increase nonlinearly with displacement. Initial shear stiffness was observed to be roughness dependent from the start. For all samples, throughout initial slip, smoother surfaces were observed to have equal or higher shear stresses than rough samples at any given displacement. Slip hardening began once the surfaces reached a fully sliding state which was signified by a yield point in the friction-displacement data. Appearance of the yield point was roughness and normal load dependent; samples with rougher surfaces and/or higher normal loads required longer displacements to reach yield (see Figure 1).

In the post-yield stage, shear strength of the surfaces continued to increase, though at a reduced rate. Slip hardening was observed to be roughness and normal load dependent. Rougher surfaces exhibited higher rates of slip hardening than smooth, and over much greater slip distances. Normal closure of the surfaces began with shear loading, being most rapid at the start of sliding and decreasing with increasing displacement (see Figure 2). We observe a correlation between the rate of closure and slip hardening; rougher surfaces exhibit higher rates of slip related closure. This suggest that slip hardening is due to increasing asperity interlock resulting from shear displacement related closure and wear of the surfaces. Friction on rougher surfaces ultimately surpassed that of smoother surfaces. Steady state coefficients of friction for the smooth surfaces reached 0.50 to 0.55, the rougher samples continued to strengthen reaching friction coefficients of 0.60 to 0.65. This coincided with the rate of normal closure reaching a minimum

Beyond 300 microns, or so, relatively stable frictional properties characterized a third stage in which friction mechanisms were probably operating near steady state.

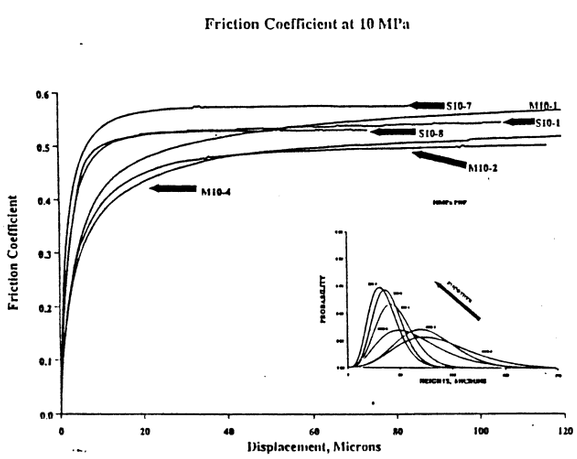

Figure 1. Friction-displacement data for 10 MPa series. At right are probability densities for the composite surface profiles, the smoother surfaces have the mean values for their PDFs to the left.

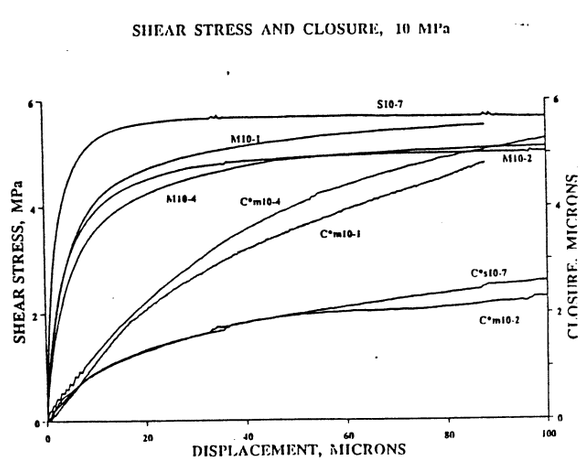

Figure 2. Closure measurements for 4 experiments in 10 MPa series with included friction-displacement data. Friction experiments have a capital M or S. Closure data is denoted by a C*.

Micromechanics of Rock Friction 2: Quantitative Modeling of Initial Friction with Contact Theory

G. N. Boitnott, R. L. Biegel, C. H. Scholz, N. Yoshioka, and W. Wang

A constitutive model is developed which predicts the mechanical properties of two rough surfaces in contact under shear with constant normal load during the early stages of frictional sliding. Upon initial application of the normal load, the model predicts that the joint consists of a finite number of contacts under a wide variety of local normal loads. As shearing develops, more and more contacts begin to fully slide, with the contacts under low local normal load sliding first (see Figure 1) This development of sliding is the cause of the non-linear force-displacement relation for deformation of the joint in shear. Two asperity scale strength laws are examined.

The model is tested with experiments on lapped surfaces of Westerly Granite with a variety of surface roughnesses and under a wide range of normal loads (10 to 35 MPa). Geometric model parameters are constrained by direct measurement of surface profiles. For both strength laws, the model quantitatively predicts the shear compliance and development of slip for the first few mic[illegible] of shear displacement, successfully describing the effect of surface roughness [illegible] load. We find that for the simple friction strength law, μ_a lies betwee[illegible] being a constant independent of normal load and surface roughness [illegible] 2). [illegible] the simple adhesion strength law, ζ is constrained to be betwe[illegible] GPa. This initial slip model helps explain the first yield point in the frictio[illegible]ve which may correspond to the gradual transition from the elastic deformation and partial slip of asperity contacts to [illegible] condition of fully sliding contacts. When a large population of contacts are fully sli[illegible]g, the model under-estimates the frictional strength, indicating that displacement [illegible]trengthening mechanisms are important.

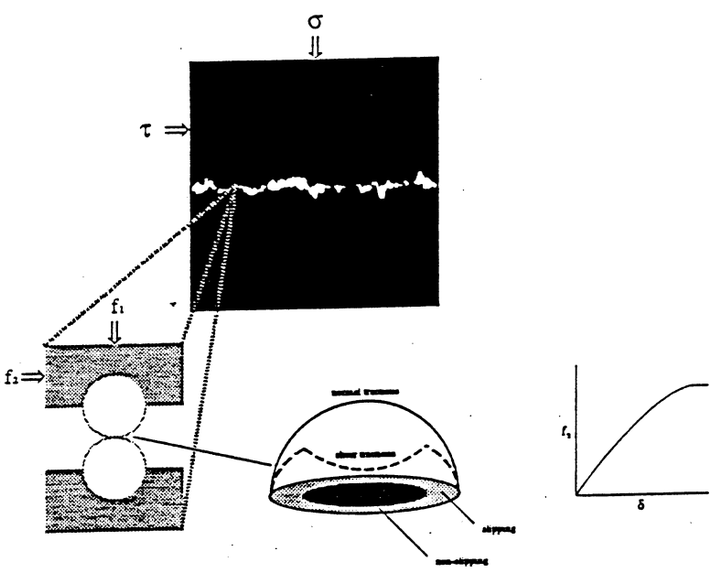

Fig. 1. Schematic illustration of the basic elements in the contact model for shear deformation. Each contact along the joint is modeled mechanically using the the elasticity solutions for two spheres given by Mindlin [1949]. Using a random process model to describe the distribution of asperities (potential contacts) on the joint [Brown and Scholz, 1985a], the number and distribution of normal loads for the population of contacts is determined for a given external normal load σ. Applying the shear force τ, the shear force verses shear displacement relationship is computed by summing the forces exerted by each asperity. At the individual contacts, the application of the shear force causes partial slip to develop at the outer edge, which propagates inward until the entire contact is sliding. The shear force (f_2) verses shear displacement (δ) for a single asperity is shown schematically. Note that the compliance of the asperity increases non-linearly with load until the contact is fully sliding.

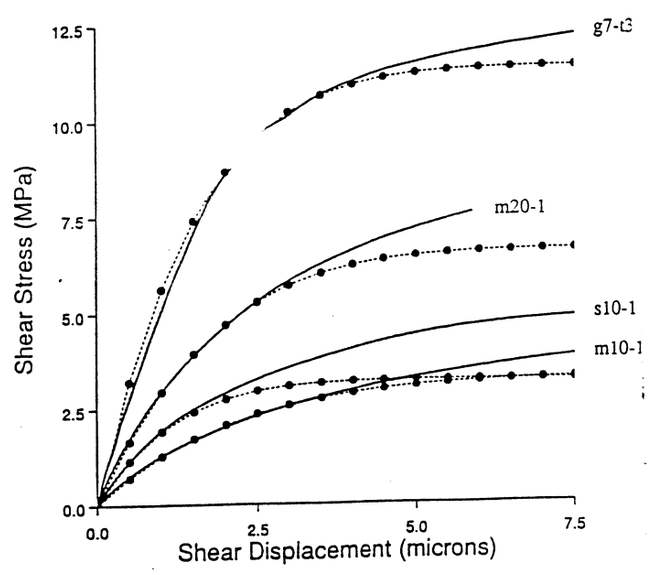

Fig. 4. Examples of model comparisons with data (solid lines) for experiments under a variety of normal loads (10 to 35 MPa) and surface roughnesses. All model results shown here are for the simple friction strength law using parameters constrained by the topography measurements. The value of μ_a is fixed at 0.33 for all results shown here. Note that a single value of μ_a is capable of fitting all experiments within the error bounds and constrained by direct topography measurements. Note that in each case, the data strengthens above the model at large displacement (1 to 3 microns). The breakdown of the model occurs at different displacements for each experiment.