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Stick-slip and creep behavior in lubricated granular material: Insights into the brittle-ductile transition

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Abstract Crustal deformation can occur via stick-slip events, viscous creep, or strain transients at variable rates. Here we explore such strain transients with physical experiments comprising a quasi-two-dimensional shear zone with elastic, acrylic discs and interstitial viscous silicone. Experiments of solely elastic discs produce stick-slip events and an overall (constant volume) strengthening. The addition of the viscous silicone enhances localization but does not greatly change the overall pattern of strengthening. It does, however, damp the stick-slip events, leading to transient, creep-like behavior that approaches the behavior of a Maxwell body. There is no gradual transition from frictional to viscous deformation with increasing amounts of silicone, suggesting that the mixed rheology is in effect as soon as an interstitial fluid is present. Our experiments support the hypothesis that a possible cause for strain transients in nature is an interstitial viscous phase in shear zones.

1. Introduction

Granular materials deform as both frictional materials and fluids at similar timescales, producing both stick-slip and creep events [Jaeger et al., 1996; Tordesillas, 2007; Dahmen et al., 2009]. Thus, granular rheology likely describes several solid Earth systems and tectonic faulting in particular [Morgan and Boettcher, 1999; Anthony and Marone, 2005; Daniels and Hayman, 2008; Mair and Abe, 2008]. Many granular systems contain interstitial fluid phases, shown to be important to fault rheology by exerting pressure and modifying friction laws [e.g., Blanpied et al., 1998]. However, the manner in which mixed viscous and frictional material lead to a specific granular rheology has been less well investigated [e.g., Higashi and Sumita, 2009]. A particularly important reason to explore such semibrittle behavior is because middle crustal rocks have long been recognized to contain mixtures of grains that behave in an elastic-plastic manner and interstitial or surrounding phases that deform via viscous deformation mechanisms [e.g., White et al., 1980]. The bulk rheology of such midcrustal rocks plays a large role in many tectonic processes, notably crustal thinning in extensional terrains [e.g., Lavier and Manatschal, 2006] and possibly the generation of strain transients [Lavier et al., 2013; Hayman and Lavier, 2014].

A useful approach to investigating mixed crustal rheology is the use of physical experiments, which allows the acquisition of large amounts of data and does not prescribe a priori rules for frictional or viscous responses. Here we use a physical model to deform a single layer of elliptical discs embedded in a viscous continuous phase in a volume-conserving simple shear apparatus [Daniels and Hayman, 2008; Hayman et al., 2011]. We describe this mixed media as a lubricated granular material [Jang and Khonsari, 2005] wherein the viscous phase decreases both the system stiffness and the characteristic length scales of deformation. With this approach we seek to answer the following: how does a weak continuous phase affect the granular deformation? What impact does the interstitial fluid have on the strain localization? And if localization and stick-slip dynamics are affected, how do they relate to the bulk rheology?

2. Granular Shear Experiments

The experimental material is a mixture of elastic elliptical discs and a linearly viscous fluid. The discs are cut from acrylic sheets and have a major axis of 10.66 mm and a minor axis of 7.2 mm. We use elliptical disks to prevent the crystallization of the granular media into a closely packed configuration. The shear strength of the acrylic polymer is $6 \times 10^4$ Pa. We ran a set of dry granular experiments (i.e., using air as the “fluid”); in all other cases we used polydimethylsiloxane (Dow Corning PDMS-DC SGM36, further referred to as silicone) with a viscosity between $4 \times 10^3$ and $4 \times 10^2$ Pa s as a fluid phase. To change the viscosity of the silicone we mixed the pure silicone with oleic acid or sand [Weijermars, 1986]. Before every experiment, we measured the silicone viscosity with a concentric cylinder viscometer [Reber et al., 2013].
The experimental chamber is pseudo two-dimensional (900 mm long, 300 mm wide, and 4 mm high) and contains a single layer of discs. The bottom of the shear cell is divided where one side is stationary and the other moving (inset Figure 1). The sliding side is string pulled and moves at a constant speed of 0.025 mm s\(^{-1}\) to a maximum shear strain of \(\gamma = 2\). The experimental chamber is covered to ensure the silicone is contained in the chamber. The cover is clear, though, allowing us to track the motion and interaction of the individual discs. The boundary conditions ensure simple shear deformation with volume conservation. To reduce the friction on the base and covering plate, we lubricate both surfaces with a water-soap mixture. We measure the pulling force on the sliding side with a Chatillon DFS II piezoelectric force gauge and the position with a Celesco cable transducer. Both are measured at a rate of 10 Hz. We document the travel path of the discs and the deformation localization by taking pictures every 15 to 60 s.

All the spaces between the discs are filled with silicone resulting in a continuous layer. In contrast with previous experiments exploring lubricated granular media [Huang et al., 2005; Higashi and Sumita, 2009], we apply simple shear conditions at constant volume. One reason for imposing a constant volume is experimental; applying dilational boundary conditions would open “holes” between the experiment material layer and the edge of the experimental box resulting in a three-phase system whenever the dilation is faster than the deformation reaction time of the silicone. In our dry experiments, this results in a buildup of forces, and steady state friction is never attained, as previously observed [Daniels and Hayman, 2008]. Though, in general, shear zones must dilate to accommodate strain, some shear zones, and ductile ones in particular, may well deform in a constant volume or volume-decreasing strengthening regime, even if for only part of their history [Means, 1995].

3. Strength Evolution

Besides the end-member dry experiment, we used four different silicone viscosities between \(\eta = 4 \times 10^5\) and \(4 \times 10^2\) Pa s. For the experiment with only silicone the viscosity is \(\eta = 4 \times 10^4\) Pa s. We repeated experiments with the same initial conditions 3 times and observed a similar overall strengthening and stick-slip behavior. Before each experiment, we distributed the discs randomly. We used a disc fraction (packing density) of \(\phi = 0.875\). This ratio between stiff and weak material ensures a system where the stiff material dominates the bulk rheology and therefore allows for stick-slip behavior [Handy, 1990]. All experiments were run until the system was too strained (discs were forced form the plane of the table) or the maximum deformation was reached, always \(\gamma > 1\).

Figure 1 displays the raw data for the force evolution versus time. In all experiments the initial force increase to 20 N is due to the loading of the spring. The experimental material did not deform at this stage of the experiment. The experiment with only silicone underwent a strong initial increase of force that evolved into a nearly constant force with time, consistent with the behavior of a nearly Newtonian fluid. All experiments that
contained discs show a stronger increase of the overall force with time, and the discs approached close packing in some parts of the box as shear proceeded. The interaction between the strong elastic discs resulted in a force increase of up to \( \approx 15 \times 10^4 \text{ N} \cdot \text{s} / \text{C}_0^3 \) with some dependence on the silicone viscosity. Finally, the measured force at a given strain weakly depended on the silicone viscosity with smaller forces for the highest fluid viscosity \( (4 \times 10^5 \text{ Pa s}) \). It seems that the presence of a viscous interstitial fluid increases the strength relative to a dry granular media.

4. Stick-Slip Behavior

Granular stick-slip events are discrete and accompany localized slip at the shear boundary in the middle of the experiment table where the basal plate is divided in a stationary and a moving side [see Daniels and Hayman, 2008]. As shown in Figure 1, the stick-slip events are superposed on what we interpret to be an experimentally produced undulation in the force curve over time; the precision limit of the force gauge defines the width of the force curves, and an undulation (a fluctuation in force that is not associated with stick-slip events) at \( >10 \text{ Hz} \) is present in all experiments including those using only silicone (bottom curve Figure 1) and are therefore not related to the interaction of the discs during deformation.

Importantly, stick-slip displacements and force drops directly correlate; we focus on force data here and briefly summarize relevant correlative slip behaviors. For the force curves produced by the dry experiment (light gray in Figure 1), after an initial loading phase, stick-slip events can be characterized by relatively long loading phases followed by short and sudden force drops. While the force drops depend on the duration of the loading phases, they are in all events short (on the order of 1 s). The coupling of the experimental table to the engine via a spring allows for a slowdown of the moving part of the experiment table during the loading phase while the force increases due to disc-to-disc elastic and frictional interactions. As soon as the applied force exceeded the frictional force between the discs, they slip past each other causing sudden force drops.

In the presence of a viscous interstitial fluid, stick-slip events occur as slow loading periods followed by slow force drops (Figure 1), for which we use the term creep events. In these experiments, we observed fewer discrete events distinguishable from the background undulation. However, the force drop is of longer duration when silicone was present (between 100 and 1500 s). As mentioned previously, the force directly correlates with displacement, and the average slip velocity for stick-slip events is 0.5 m/s, whereas the average velocity for creep events is 0.01 m/s.

The silicone viscosity does not seem to greatly impact velocity of the force drop. The shapes of the individual events, however, are dependent on the silicone viscosity. Figure 2 shows close-ups of the slip events of three different experiments. The events of the dry experiment show a sawtooth shape with very sharp and fast force drops. This behavior can also be observed at a larger scale in Figure 1 where one large slip event at \( 4 \times 10^4 \text{ s} \)
dominates the curve. The amplitudes of these events vary between less than 1 N and 10 N. The slip event shown for the experiment with a silicone viscosity of $4 \times 10^3$ Pa s displays a clear concave shape during the force release phase with amplitude varying between 1 and 3 N. With an increase of the silicone viscosity ($4 \times 10^5$ Pa s), the slip events get less prominent and become difficult to distinguish from the background undulation with amplitude of less than 1 N.

Though there is a clear difference recorded by the force curve in the presence of an interstitial fluid, we did not observe a gradual transition between the stick-slip and the creep events, as it is not possible to conduct experiments on our shear apparatus with fluids of a smaller viscosity than the one we used.

5. Effect of Fluid on Localization

As deformation localized into the central shear band, the shear-band width was strongly dependent on the weak phase (Figure 3), from approximately six discs wide in dry experiments to approximately two to three discs for silicone-present experiments; deformation of pure silicone did not lead to localized shear band development. Localization occurred early in the experiments and remained stable over the entire experiment. There was, however, a subtle undulation of the shear band over time where they moved slightly away from the experiment center depending on the disc distribution and location with respect to the stationary and moving experiment table, respectively. Discs that were not involved in the shear band were stationary or moved at the speed of the moving plate. Counterintuitively, where one might suspect that the deformation delocalizes when a viscous fluid is added, our experiments show that the deformation localizes strongest when a viscous fluid is present (Figure 3).

6. Bulk Rheology

To investigate the bulk rheology of the material mixture, we explore two parameters: the effective viscosity and a measure of the ratio between frictional and viscous forces called the Leighton number [Huang et al., 2005]. To calculate the effective viscosity of the material mixture, we use the Marone-Pierce-Kitano (M-P-K) model [Barnes, 2003] for a Newtonian continuous phase and densely packed particles:

$$\eta_{\text{eff}} = \eta_0 \left(1 - \frac{\phi}{\phi_m}\right)^{-2}$$  \hspace{1cm} (1)

where $\eta_0$ is the viscosity of the weak interstitial phase, $\phi$ the disc fraction, and $\phi_m$ the maximum disc fraction [Delaney et al., 2005]. As we kept the disc fraction constant in our experiments, and as we used the same disc size and shape, $\phi$ and $\phi_m$ are constant. The effective viscosity therefore changes with the same orders of magnitude as the viscosity of the fluid. We find that the effective viscosities for the cases with silicone range from $8 \times 10^5$ to $8 \times 10^8$ Pa s.
The Leighton number ($Le$) is defined as

$$Le = \frac{\eta \dot{\gamma}}{\sigma}$$

where $\dot{\gamma}$ is the shear strain rate and $\sigma$ the shear stress. According to Huang et al. [2005], whenever the Leighton number exceeds a critical value of $L_{ec} \approx (7 \pm 5) \times 10^{-4}$, the deformation takes place as viscous flow. In order to evaluate the Leighton number, we first estimate the shear stress in the experiments by assuming that the area on which the deformation is localized and where the slip occurs has the length of the experimental chamber, the width of the shear band, and the height of the granular layer. For the experiments with a silicone viscosity of $4 \times 10^3$ Pa s and $4 \times 10^2$ Pa s, we obtain a value for $Le = 4.65 \times 10^{-5}$ and $4.48 \times 10^{-6}$ respectively. These values are smaller than Huang’s [2005] $L_{ec}$, indicating that the deformation is influenced by the frictional flow. This can also be observed in Figure 1 where force curves show discrete events. For the experiments with stronger silicone ($4 \times 10^4$ and $4 \times 10^5$ Pa s), $Le$ is larger than $L_{ec}$ indicating that the deformation can be described as viscous flow. By investigating the force curves (Figure 1), however, we still observe small events and note that the deformation becomes localized, even during what is defined as viscous flow according to the Leighton number. These observations indicate that the deformation cannot be described as a pure viscous flow but that the discs still have an influence on the overall deformation even though $Le$ is larger than $L_{ec}$. Thus, the Leighton number might be too simplistic to describe the behavior of a lubricated granular media.

To summarize, Figure 4 shows the three parameters that we measured in our experiments: the width of the shear zone (localization), the effective viscosity ($\eta_{eff}$), and the Leighton number ($Le$). This diagram shows that the four experiments with interstitial silicone plot close together and behave in a similar way. $Le$ decreases while the localization increases for an increasing viscosity of the silicone. The dry granular experiment plots in the same trend as the experiments with silicone, illustrating that it is an end-member case of the same experimental series. In contrast, the experiment with only silicone and devoid of any discs behaves fundamentally different which is reflected in Figure 4 where the localization and the Leighton number are zero.

7. Discussion

With physical simple shear experiments on a granular-viscous material mixture, we explored the effects of an interstitial viscous phase on the stick-slip dynamics and localization in a granular system and their impact on bulk rheology of a wet granular media. By comparing the deformation of a mixed granular media to a dry granular media, our experiments show that the shapes of stick-slip events are dependent on the interstitial fluid. While the dry experiment shows classical stick-slip events [Jaeger et al., 1996], the experiments with silicone show a smoother force curve [see also Higashi and Sumita, 2009]. Whenever the force generated by the jamming of the discs exceeds the viscous resistance of the silicone plus the frictional resistance of the discs, a sudden change in strain followed by displacement along the shear zone occurs (Figures 1 and 2). We define such relatively slow events as creep events that result in displacement across the shear zone following a sudden strain. There are two possible in situ mechanisms for the slip behavior including slip-rate changes, strengthening, and localization. One is that shear must overcome both the disc-to-disc interaction as well as the viscous resistance of the interstitial fluid. The other is that the interstitial fluid acts on the granular media affecting...
thereby the force distribution. Regardless of the precise mechanism, we can describe the bulk rheology using a formulation proposed by Lavier et al. [2013] wherein the decay time at the location of the creep event is a function of the shear modulus, $G$, and the viscosity of the viscoelastic material, $\eta_{\text{eff}}$, in which the event occurs (in our case the disc + viscous fluid) as well as the viscosity of the fluid layer, $\eta_w$ over which the creep event occurs:

$$T_{\text{decay}} = \frac{H_w:\eta_w}{2G(\eta_{\text{eff}} + \eta_w)}$$

(3)

where $H_w$ is the thickness of the fluid layer and $H_b$ the thickness of the upper plate riding over the shear zone. Since in our experiment $H_w < H_b$, we can neglect $\eta_{\text{eff}}H_w$ in the denominator of equation (3), and we obtain $T_{\text{decay}} = \frac{\eta_w}{2G}$. The decay time is now equivalent to that of a viscoelastic material responding to sudden stress increment at constant strain (local). Using the effective viscosities $\eta_{\text{eff}}$ determined by using the M-P-K model ($8 \times 10^5$ to $8 \times 10^8$ Pa s) and the shear strength of the discs $G = 6.4 \times 10^4$ Pa, we find relaxation times ($T_{\text{decay}} = \eta_{\text{eff}}/2G$) vary between ~10 s and 10,000 s. These numbers are similar to those observed for the creep events in the experiments (10 s to 1500 s, Figure 2). The relatively good match between viscoelastic decay time and the measured decay time is surprising since the M-P-K model ignores the fact that the strength of the material is also partly supported by elastic and frictional interactions. We can also remark that for a high-viscosity fluid the force necessary to deform the material is lower than for a low-viscosity fluid. This suggests that disc-to-disc interaction is larger in a low-viscosity fluid than in a high-viscosity fluid and that the simple viscoelastic relaxation model is best suited for high-viscosity materials.

The other possible measure of the bulk rheology is the Leighton number. While two of our experiments show $Le$ values smaller than $Le_c$, the other two experiments show $Le$ larger $Le_c$, suggesting that only the two experiments with lower viscosity silicones ($\eta = 4 \times 10^2$ and $4 \times 10^3$ Pa s) are dominated by frictional forces. We observe that the overall system behaves more ductly with an increase of the silicone viscosity, but in these high-$Le$ cases the deformation cannot be described as purely viscous as we still see events that are caused by the disc interactions in addition to the strong localization of the deformation. This suggests that the Leighton number cannot be used as a sole determination whether the deformation is governed by frictional or viscous forces, but a more complete constitutive expression is needed.

We also find that adding a viscous fluid into an elastic frictional granular media increases localization. In dry granular media the shear-band width is known to be controlled by compaction length scales [Francois et al., 2002] and is typically 6 to 10 grain or disc diameters wide under hydrostatic pressure. Whenever there is an interstitial fluid present, the experiments show a stronger localization of the deformation where the shear band is only two to three discs wide. Higashi and Sumita [2009], using silicone viscosities of 0.85 to 11400 mPa s, observed that the addition of a fluid decreases the width of the shear band by half, which corresponds to our findings. Our results show that also for a higher silicone viscosity (between $4 \times 10^5$ and $4 \times 10^3$ Pa s), the width of the shear band is thinner than in dry granular experiments, indicating that localization occurs for fluids with viscosities spanning 10 orders of magnitude. The presence of a fluid provides a new controlling length scale for the shear-band width that is likely proportional to the fluid viscosity.

The viscosity contrast between the discs and silicone is comparable with the viscosity ratios between quartz and feldspar in experimental approximations of midcrustal shear (e.g., $T > 200°C$, $P > 28$ MPa, at experimental strain rates of $10^{-14} \text{ s}^{-1}$) [Shelton and Tullis, 1981; Brace and Kohlstedt, 1995]. This suggests that a similar mixed rheology might be at play in midcrustal conditions. For example, a recent analytical model explains measurable strain transients as a result of a creeping granular media with contrasting viscosities [Lavier et al., 2013]. The fact that there is no gradual transition from frictional to semibrittle behavior with lubrication in our experiments suggests that the presence of even minor amounts of interstitial viscous material can cause such transients. In turn, the stick-slip dynamics of faults in the middle to upper crust will change with the introduction of a viscous media, potentially changing the coseismic release.

8. Conclusion

Our experiments show that the presence of an interstitial fluid in a granular media strongly affects the stick-slip behavior of the system and the localization of the deformation. An increase of the interstitial fluid viscosity leads to a stronger damping of the stick-slip events and to a more viscous-like behavior, approximated by a simple M-P-K viscoelastic model. However, even with the addition of a viscous material, we can still observe the impact of frictional interactions between discs. In the presence of a fluid phase the
deformation is more localized than in a dry granular case. However, we cannot observe an instantaneous change, such as measured by a Leighton number, from frictional to viscous deformation suggesting that a mixed rheology is in effect as soon as an interstitial fluid is present and defines a transitional behavior across a range of viscous media concentrations. Our experiments suggest that in crustal systems where a mixed brittle-ductile rheology is at play, localization can be efficient, frictional responses can be dampened but still present, and basic rheological descriptions may apply, all of which has implications for understanding strain transients and coseismic release.

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