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A NOTE ON THE FRICTIONAL STRENGTH OF LAUMONTITE FROM CAJON PASS, CALIFORNIA

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Abstract. Laumontite mineralization is pervasive in joints and shear zones encountered in the Cajon Pass drillhole in southern California. In order to determine whether a gouge composed of this hydrated mineral affects shear strength in a manner similar to low–strength, clay–rich fault gouges, frictional sliding experiments were performed under dry, saturated and high pore pressure conditions at effective pressures up to 450 MPa. Coefficients of friction ranged between 0.66 and 0.84, consistent with most crustal rocks and well above the values typical of clay–rich San Andreas fault gouges. Saturation state had no effect on strength or sliding stability. These results suggest that the presence of laumontite in shear zones at Cajon Pass will not affect the shear strength of the rock in a way that can account for the inferred low ambient shear stresses.

Introduction

Mineralogical investigations of cuttings and core samples from the DOSECC Cajon Pass drillhole in southern California near the San Andreas Fault show that zeolite mineralization is pervasive throughout the drillhole. The zeolite mineral laumontite occurs as a fracture–filling mineral and as a replacement of plagioclase within the host rock. Zonation and cross–cutting features suggest that the zeolitization has been episodic in nature, and that it is one of the more recent events in the geologic history of the region, postdating the folding and most of the faulting. This mineralization appears to be geographically associated with the San Andreas, extending laterally to a distance of 4 km from the fault, with the most pervasive alteration within 1 km. Emplacement of the laumontite is attributed to the circulation of groundwater within fractures and frictionally heated rocks along the San Andreas, at temperatures between 140 and 190°C [*Vincent and Ehlig*, 1988].

It has been suggested that the alteration and veining of the rocks at Cajon Pass may cause major changes in rock properties, such as a reduction in permeability, variations in the pore fluid composition, and changes in the elastic, shearing or ductile properties [*James and Silver*, 1988]. Certain of these effects have been investigated. For instance, *Morrow and Byerlee* [1988] found that the healing and sealing of fractures in granodiorite from Cajon Pass by laumontite and other hydrothermal minerals reduced the permeability to values of less than 10^{-21} m^2 at *in situ* pressures. This is several orders of magnitude lower than values typically reported in the literature for granitic rocks under similar conditions. Such low permeabilities may be an important factor in the observed isolation of chemically distinct pore fluids in different fracture zones within the drillhole [*Kharaka et al.*, 1988]. Pervasive alteration of minerals within the host rock to laumontite was also found to reduce the strength of intact cores, as well as reduce the P and S wave velocities through the rock [*Vernik and Zoback*, 1989]. The effect of laumontite mineralization on the shearing behavior of the rock is of particular interest, because some coherent zeolite–filled joints show evidence of movement, and laumontite is also abundant in many fault zones encountered in the drillhole [*James and Silver*, 1988]. These observations suggest that in some regions, the laumontite may act as fault gouge in joints and faults along which strain in the rock is accommodated.

Because laumontite formation is associated with the San Andreas Fault, it is pertinent to determine whether the frictional strength of this mineral is typical of most other crustal rocks and rock–flour gouges, with a coefficient of friction of 0.6 to 0.85, or whether the hydrated nature of the mineral may cause anomalously low frictional strengths that are more characteristic of clay minerals [*Byerlee*, 1978]. Low–strength fault gouges are often cited as a possible explanation for the "stress–heat flow paradox" regarding the strength of the San Andreas Fault. This debate has come about because conductive heat flow measurements, *in situ* testing and seismic stress drops suggest that the average shear stress on the fault is around 10–20 MPa, whereas faulting theory and laboratory–derived shear strengths of crustal rocks suggest that fault strength should be on the order of a few hundred MPa [*Zoback et al.*, 1987]. These constraints can be reconciled if fluid pressures are above hydrostatic in the gouge zone, or if the coefficient of friction of the gouge material is around 0.2 or less. In order to investigate the latter possibility, we have undertaken a series of frictional sliding experiments to measure the coefficient of friction of laumontite gouge from Cajon Pass, California. The results are compared with the strengths of other gouge minerals found along the San Andreas Fault.

Sample Description and Procedure

The laumontite used in this study was collected from surface outcrops near the scientific drillhole at Cajon Pass, California, where it occurs as veins in a granodiorite. These surface outcrops are similar in character to the laumontite found at depth throughout the drillhole. The laumontite veins were separated from the crystalline matrix and crushed into granular form. X–ray analysis shows that the gouge is nearly pure laumontite, with mi-

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nor quartz and feldspar derived from the matrix.

Samples of Westerly Granite were machined into cylinders 2.5 cm in diameter and 6.3 cm long, containing a 30° sawcut. Westerly Granite was used in these experiments to simulate the granodiorite host rock at Cajon Pass. The sawcut was filled with a 1-mm-thick layer of crushed laumontite, and the two granite halves were held together with a thin copper jacket. A small hole in the center of the upper granite piece allowed water in the pore pressure system to communicate more easily with the laumontite gouge during the experiment. This gouge/rock assembly was placed in a vacuum oven at 100°C for 24 hours to dry the gouge layer completely. The sample was then placed in a polyurethane jacket and fastened to the steel endplugs with wire clamps.

Frictional sliding experiments were conducted under room temperature conditions, with effective pressures ranging from 30 to 450 MPa. These tests were designed to duplicate experiments conducted by *Radney and Byerlee* [1988] on low-permeability clay gouges. For the clay tests, it was important to begin the experiments in a dry state to avoid overpressuring the clay during the initial loading of the sample. This was not a problem with the laumontite gouge, because the permeability of the sample was high enough ($> 10^{-15} m^2$) that fluid pressures could equilibrate quickly. For the sake of uniformity, the laumontite samples were also run in an initially dry state. Confining pressure was applied to the sample, and sliding proceeded at an axial displacement rate of 0.866 μ/s. This corresponds to a shear-displacement rate along the gouge layer of 1 μ/s. After 2.5 mm of axial displacement, the piston was held fixed for 10,000 s, after which sliding continued to a maximum value of 7 mm. Three series of experiments were conducted following this standard procedure. In the first series, the samples remained dry throughout the run. In the second series of experiments, deionized water was introduced to the sample during the pause. In this way, the wet and dry strength could be compared at the same pressures. For the last series of experiments, fluid pressure was introduced to the dry sample during the pause at a value equal to one third of the confining pressure, simulating a typical hydrostatic-to-lithostatic pressure ratio at depth.

Results

The coefficient of friction as a function of axial displacement for the dry samples is shown in Figure 1. More shear strain was required at each higher pressure to reach a steady-state strength. The 10,000 s pause caused a slight drop in the strength, as the samples began to creep under the sustained load. When sliding was resumed, the gouges regained their initial strength after a small transient peak. At the two highest pressures, the samples failed by stick slip and did not regain their full shear strength by the end of the run. With the exception of the 30 MPa sample, the coefficient of friction decreased systematically with increasing confining pressure. Once steady-state sliding was reached, the values ranged between 0.66 and 0.80 over pressures from 30 to 450 MPa.

Samples that were saturated at room pressure during the pause are shown in Figure 2. Saturation caused

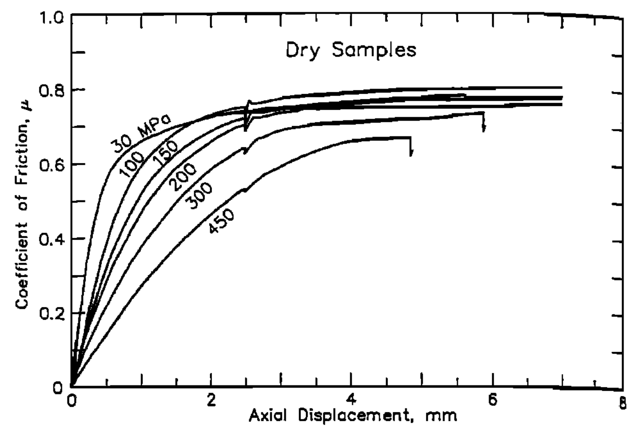

Fig. 1. Coefficient of friction of vacuum-dried laumontite samples, with a 10,000 s pause at 2.5 mm displacement. Confining pressure indicated along curves.

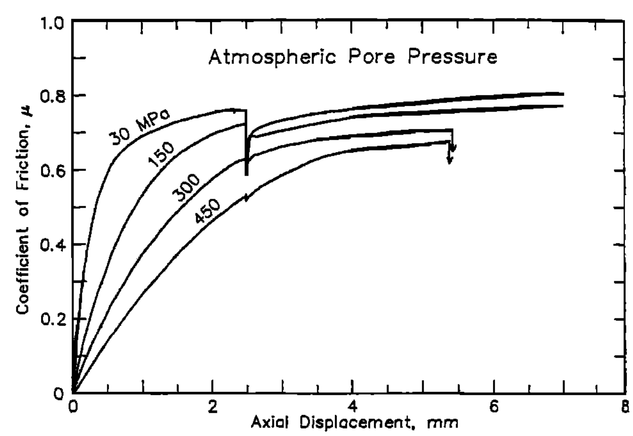

Fig. 2. Coefficient of friction of laumontite samples saturated with deionized water at 2.5 mm displacement. Confining pressure indicated along curves.

a pronounced drop in strength at the lower pressures, which eventually recovered to the same values as observed in the dry runs. The coefficient of friction at higher pressures was unaffected by the introduction of water. These samples also failed by stick slip before the end of the experiment. Here again, the coefficient of friction ranged between 0.66 and 0.80 over the pressures studied.

Frictional sliding runs in which the fluid pressure was added to simulate upper crustal conditions are shown in Figure 3. Here the effective pressure, defined as the difference between the confining and pore pressure, P_c-P_p, was used to calculate the coefficient of friction after the pore pressure was introduced. Because the coefficient of friction is dependent on pressure, friction values increased after saturation due to a reduction in the effective pressure acting on the samples. This change was more pronounced at the higher pressures because of the differences in the displacement at which the steady-state strength was attained. Friction values ranged between 0.74 and 0.84 for these samples. This series of runs proves that the effective pressure law for friction holds for laumontite. That is, the coefficient of friction is a function of the effective pressure, regardless of the

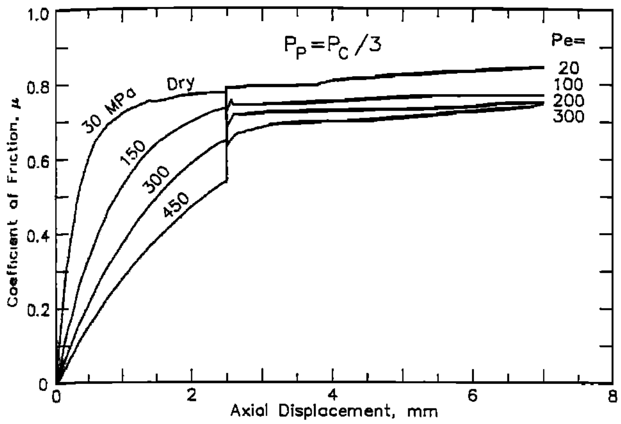

Fig. 3. Coefficient of friction of laumontite samples saturated with deionized water at 2.5 mm displacement. Pore pressure was raised to one third of the confining pressure, effective pressures for the saturated portions are given at right.

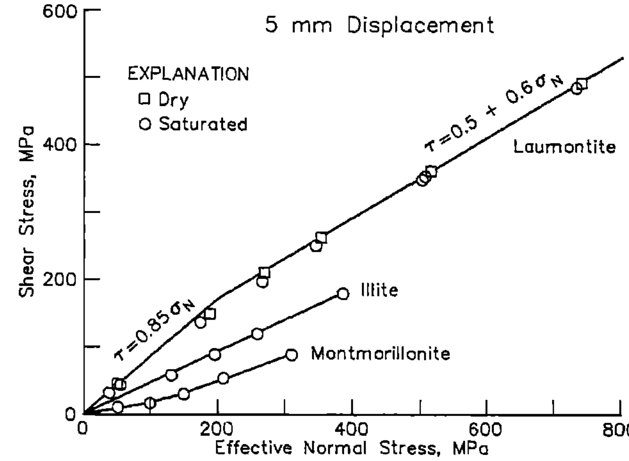

Fig. 4. Shear and effective normal stress relations at a shear displacement of 5 mm, for laumontite and clay gouges.

choice of confirming and pore pressures (compare 300 MPa, Figures 2 and 3). This common assumption was previously untested for laumontite.

The three series of sliding experiments verify that the coefficient of friction of laumontite is high (0.66 - 0.84 for the conditions of this study), and that the strength and stability of this hydrated mineral is not affected by the presence of fluids. Shear and normal stress data for these experiments taken at 5 mm of shear displacement (Figure 4) demonstrate that laumontite closely follows the friction relationship reported by *Byerlee* [1978], and therefore this gouge has frictional characteristics that are similar to most other crustal materials. This friction relationship is indicated by the lines $\tau = 0.85\ \sigma_n$ below normal stresses of 200 MPa, and $\tau = 0.5 + 0.6\ \sigma_n$ for normal stresses above 200 MPa. Strength data for the gouges composed of montmorillonite and illite are shown for comparison, also at a displacement of 5 mm. These samples have undergone the same frictional sliding history as the laumontite. Montmorillonite and illite are common constituents of fault gouges found along the San Andreas, and are representative of the lower and upper bounds of the coefficient of friction observed in clay-rich gouges. These clays were both weaker than the laumontite, with a coefficient of friction of 0.2 to 0.3 for the montmorillonite and 0.4 for the illite under saturated conditions to effective pressures of 300 MPa.

Discussion

The strength and stability of fault gouges have been found to correlate with the type and orientation of deformation structures formed within the gouge zone [*Moore et al.*, 1989]. The gouges shown in Figure 4 are no exception, as petrographic observations show that the fabric and shear band development of each gouge type tracks well with the applied confining pressure. However, certain questions remain which are difficult to explain in terms of the larger deformation features alone. For instance, why was the shear strength of the laumontite gouge unaffected by the presence of fluids in spite of the hydrated nature of the mineral? Also, why was there such a difference in strength between the three gouge minerals? These questions can better be explained by looking on a smaller scale at the structure of the gouge minerals themselves.

Laumontite is a framework aluminosilicate consisting of rings of $(Si/Al)O_4$ tetrahedra, which link in a complex way to form cavities and channelways through which ions can easily exchange or pass. Bonded water is loosely attached to the interior of the channelways, and can be removed or replaced without disturbing the framework bonds. This structure is in marked contrast to the sheet structure of the clay minerals which are typically found in fault zones. Crystal structure, while not generally a strength–controlling factor, becomes important when the effect of water is considered. Because the bonded water is internal to the framework of the laumontite in a network of "tubes", it does not have as significant an influence on the frictional sliding properties between the grains as water that bonds into more organized layers. This may account for the fact that the dry and saturated laumontite runs shown in Figure 4 had the same strength.

In contrast, bonded water in the expandable clay montmorillonite forms planes between the structural layers and on the surface of the grains, which act as glide planes to facilitate slip. This significantly reduces the frictional shear resistance of the gouge, as *Bird* [1984] demonstrated in frictional sliding experiments on montmorillonite with varying numbers of bonded water layers. He found that montmorillonite becomes slightly stronger at higher normal stresses, because successive water layers are squeezed out with increasing pressure, and the last few water layers are more tightly bonded and difficult to remove than the first ones. This strengthening behavior corresponds to the upward curvature of the montmorillonite data in Figure 4. The non–expandable illite does not exhibit this increase in strength with pressure, as shown by the linear trend in Figure 4. However, saturation was found to reduce the strength of illite as well because of the adsorbed water on the surface of the platelets [*Radney, Morrow* *and Byerlee*, unpublished data, 1989]. Thus, the location of the bonded water may be an important factor which contributes to the different frictional responses of the gouges. As a consequence, the coefficient of friction of the laumontite gouge was higher than that of typical clay-rich fault gouges, and is consistent with the strength of other natural gouges compose of crushed schists and granitic rocks [*Morrow et al.*, 1984].

The results of these frictional sliding experiments must be placed in the context of the *in situ* environment at Cajon Pass. Other factors may influence the frictional strength which were not addressed in these experiments, such as velocity dependence, temperature and chemical effects. Some general comments regarding these factors are warranted. Many geologic materials exhibit a slight change in strength when the sliding rate is varied. This velocity dependence, while fairly small at low temperatures, has been shown to be significant at temperatures above 300°C [*Stesky*, 1978]. Because this is above the stability field of laumontite, which dehydrates at around 200°C (depending on pressure) to form the mineral wairakite, velocity dependence is probably not a critical factor under *in situ* conditions of slip rate and temperature.

Temperature affects the strength of some materials in other ways as well. *Moore et al.* [1983, 1989] found that an increase in temperature caused an increase in frictional resistance of clay gouges towards those values typical of crystalline rocks, due to induration of the samples. Temperature had little effect on the strength of gouges derived from strong crystalline rocks. This suggests that granular laumontite may continue to display a high shear resistance at elevated temperatures in a manner similar to crushed granite. Based on the P-T stability of laumontite [*Liou*, 1971], we would expect this mineral to be most relevant in the mid and upper portions of the seismogenic zone in the vicinity of Cajon Pass, well out of the range of depths and temperatures where strain softening mechanisms come into play.

James and Silver [1988] suggest that laumontite may influence the geophysical properties of rocks in and near the San Andreas Fault, which may ultimately affect the seismic behavior of the fault. Although the presence of laumontite has been shown to alter certain rock properties, the friction studies of laumontite gouge do not reveal any behavior that differs from that of other typically strong rocks. These results suggest that joints and fault zones that are filled with laumontite will follow the friction relationship reported by *Byerlee* [1978] under normal hydrostatic and lithostatic conditions. As a result, the presence of laumontite in shear zones is unlikely to influence the shear strength of the rock in a way that would contribute to the of low ambient shear stresses at Cajon Pass, California, that were reported by *Zoback et al.* [1987].

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