T41F–1306

Interpreting the Frictional Behavior of the Smectite Clay Montmorillonite

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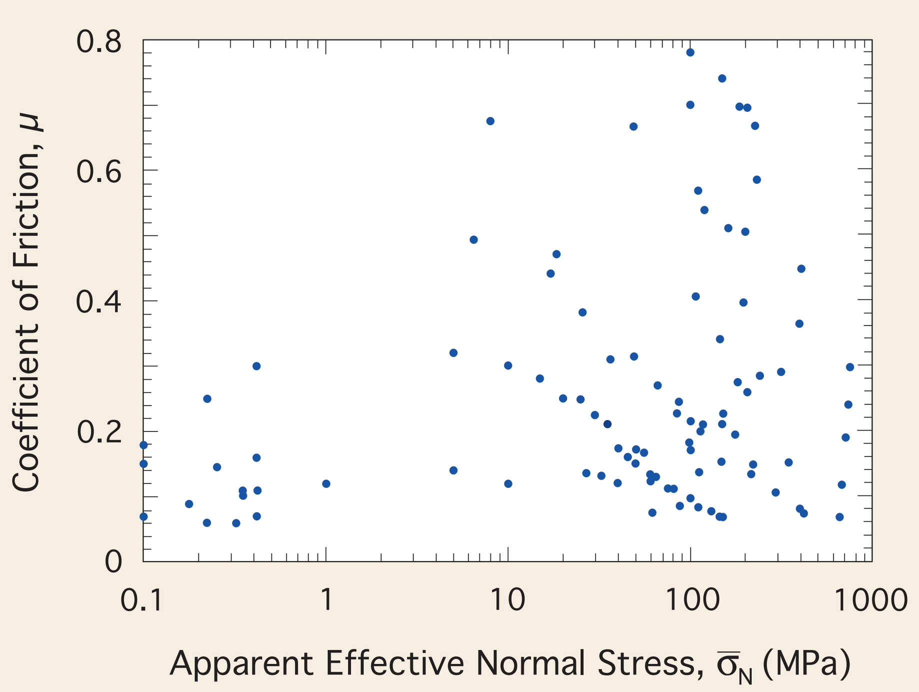
USGS science for a changing world

Abstract

Montmorillonite has been the most widely tested phyllosilicate mineral in soil and rock mechanics friction investigations, but many of the published data are contradictory, with reported values of the coefficient of friction, μ (= shear stress/effective normal stress) ranging from 0.06 to 0.78. We report some new laboratory and petrographic data which illustrate that this wide variation is in part a function of the large difference in coefficient of friction between thoroughly dried ($\mu \geq 0.7$) and water-saturated ($\mu \leq 0.3$) montmorillonite. Dry montmorillonite gouge is subject to standard frictional processes such as abrasion, wear, and fracture during shear. In contrast, shear of water-saturated montmorillonite gouge is concentrated in thin films of water that are adsorbed onto the (001) surfaces of the platy grains. Our recent studies suggest that the water-saturated shear strength of sheet-structure minerals increases with the strength of the bonding of the polar water molecules to the (001) surfaces, and the relative weakness of water-saturated montmorillonite may be largely owing to its small layer charge. Values of μ for montmorillonite that are considered to represent water-saturated, equilibrated conditions increase from 0.06 at effective normal stresses <1 MPa to 0.30 at 300 MPa. This correlation is attributed to decreasing thickness of the surface water films with increasing effective normal stress. Similar stress dependence of frictional strength can be demonstrated for the serpentine minerals, muscovite, biotite, phlogopite, chlorite, kaolinite, and talc, and it is considered to be characteristic of sheet silicates. This behavior contrasts with that of most other silicate minerals, for which μ exhibits little pressure sensitivity below 200 MPa effective normal stress and then decreases at higher stresses (Byerlee's law).

Most of the published strength data for montmorillonite fall outside the range of values for water-saturated, equilibrated samples. Of these, the samples that are overly strong for a given set of experimental conditions may have been only partially saturated. Those samples that are weaker than the water-saturated, equilibrated samples at a given effective normal stress appear to result from inadequate drainage and consequent build-up of internal pore pressure. The velocity dependence of montmorillonite strength has not been extensively investigated, but water-saturated montmorillonite gouge is velocity-strengthening over the range of conditions tested to date, whereas dry and partially saturated montmorillonite gouge may be velocity weakening at some velocities. These results highlight the hazards of interpreting fault-zone behavior based on experiments that do not approximate natural conditions.

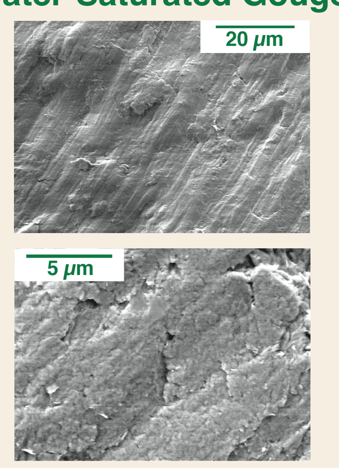
Compiled Strength Data for Montmorillonite



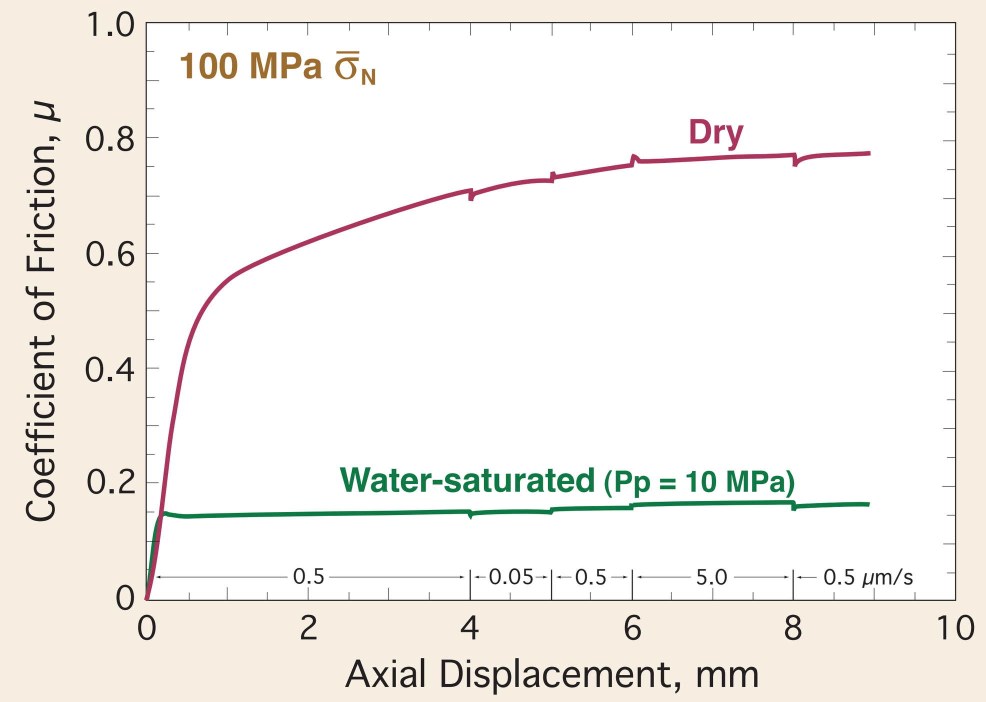
This figure summarizes the reported room-temperature strength data for montmorillonite from soil- and rock-mechanics studies (sources are identified in figures at right). Many of the published strength data are contradictory; between 100 and 150 MPa, for example, μ varies by more than an order of magnitude. This wide range is too large to be explained by differences in sample composition or systematic errors in test procedures. In this poster, we offer explanations for the apparent contradictions among the existing data, based on our recent investigations of the dry and water-saturated frictional strengths of sheet-structure minerals combined with the earlier work of Wang et al. (1980).

Dry Versus Water-Saturated Montmorillonite Strength

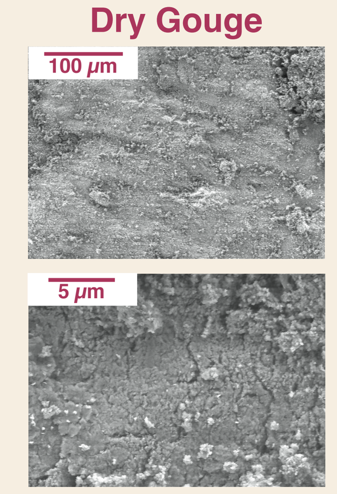
Water-Saturated Gouge



The water-saturated gouge contains well-developed, shiny and slickensided shear surfaces, and (001) surfaces of the clay grains in the shears are oriented parallel to the shear planes. (All four photos are secondary-electron SEM images.)

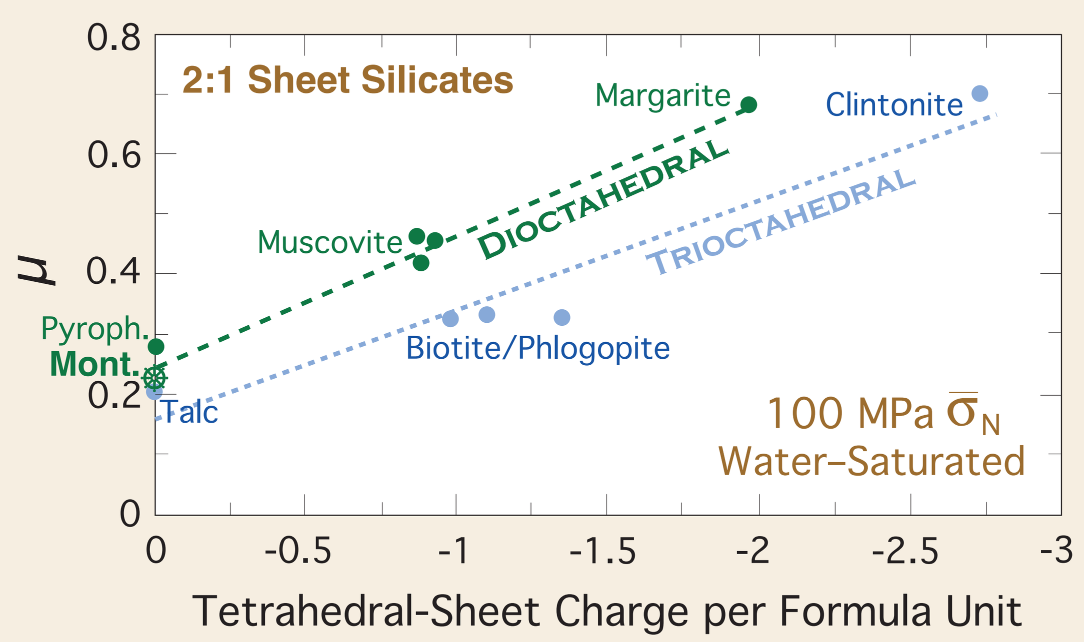


Dry Gouge



Shear surfaces of the dry gouge sample are considerably rougher and grainier in appearance than those in the water-saturated gouge, and preferred orientation of the platy grains in the shears is only locally evident.

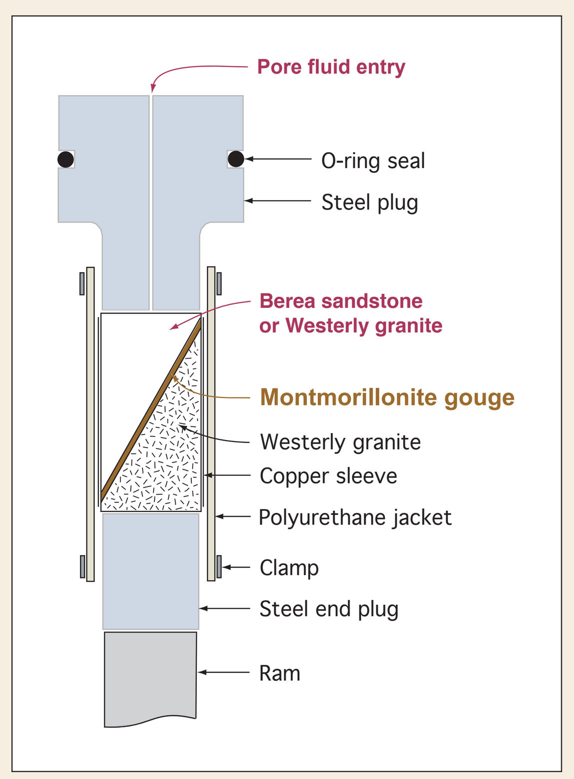
A major feature of montmorillonite friction is the very large difference between dry and water- saturated strengths, as illustrated above by the two triaxial friction experiments using a pure Na- montmorillonite gouge. The samples were vacuum-dried for ≈22 hours at 125°C and then immediately jacketed and placed in the pressure vessel. For the water-saturated sample, deionized water was introduced at 10 MPa fluid pressure after application of the confining pressure. At these conditions, μ of dry montmorillonite is ≈4 times as large as μ of water-saturated montmorillonite.



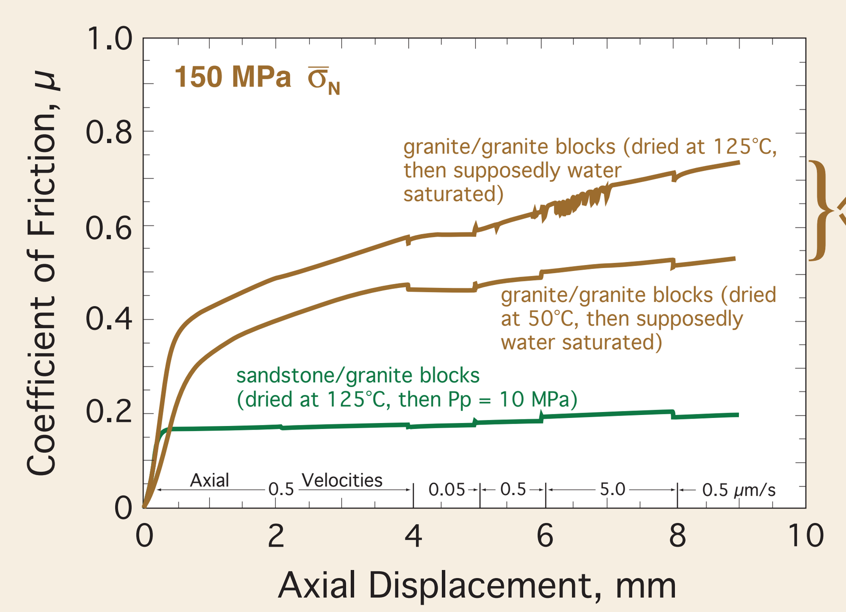
For sheet silicates, the bonding within a layer is strong whereas the (001) bonds that hold the layers together are relatively weak. As a result, these minerals have a perfect cleavage parallel to (001) and usually a platy morphology. The (001) bond strengths and the shape anisotropy of these minerals are important factors in controlling their frictional strengths. We (Moore and Lockner, 2004) concluded that the shear of phyllosilicate-rich gouges is concentrated in thin films of water adsorbed onto the (001) planes that line the shear surfaces. The shear strength of the water films is a function of the degree of attraction of the water molecules to the (001) planes; specifically the strength is correlated to factors that contribute to the electrostatic component of the interlayer bond. Some of those relationships are illustrated at left; montmorillonite strength is consistent with its dioctahedral structure and the concentration of its small layer charge in the octahedral rather than the tetrahedral sheet.

We also found a relationship between the calculated interlayer bond strength and μ (dry) of layer-structure minerals; for minerals with μ (dry) < 0.8 shear occurred by cleaving through the (001) planes. Based on its crystal structure, dry montmorillonite was expected to be weak. Its unexpectedly high dry strength may be owing to the extremely thin crystals: a grain that is only one unit cell thick cannot cleave through the interlayer bonds. The grainy shear surfaces of the dry montmorillonite sample are similar to those of other phyllosilicates for which μ (dry) ≈ 0.8.

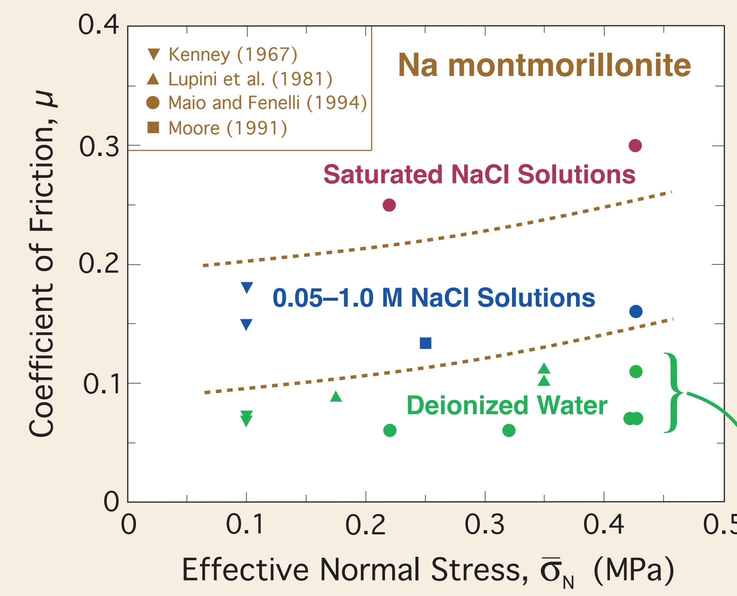
Experimental Assembly and Strength

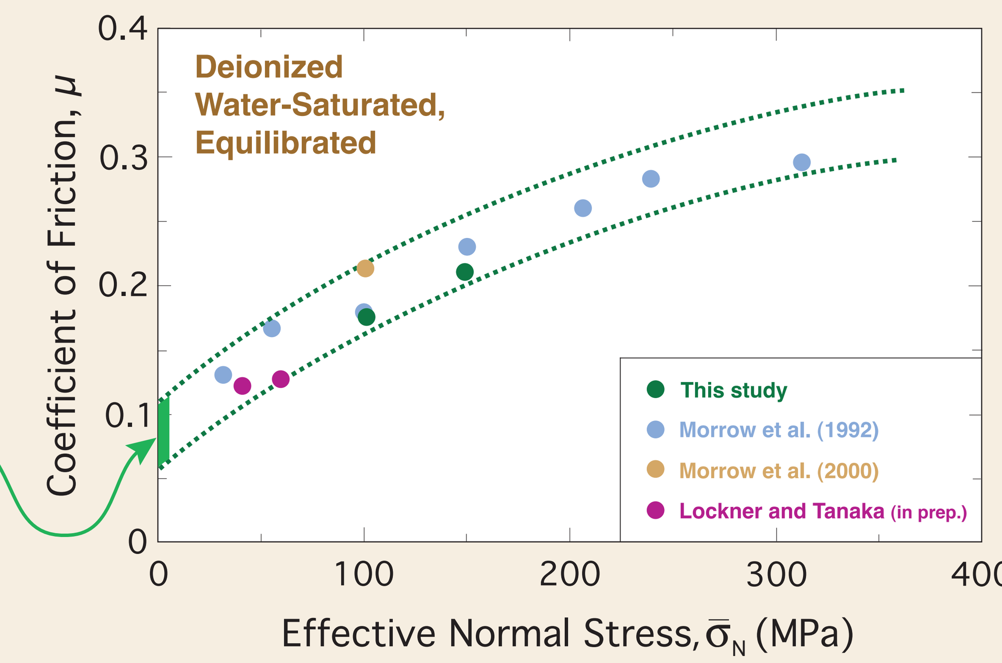


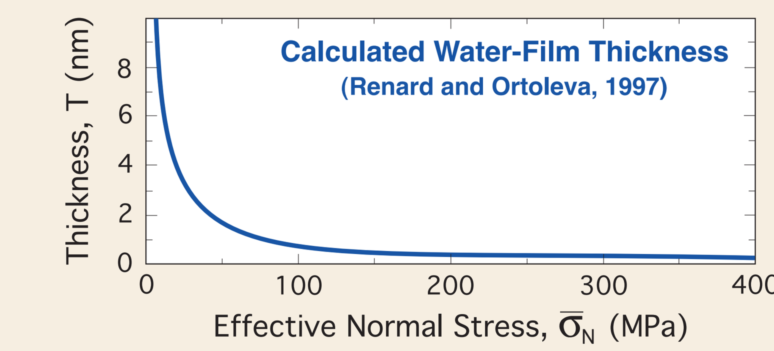
The pore-fluid set-up for a triaxial friction experiment critically affects the measured strengths. Pore fluid is introduced to the top of the upper forcing block and then must diffuse through that piece to reach the gouge layer. In the same way, excess fluid pressure in the gouge is alleviated by flow back across the upper forcing block. Berea sandstone was used for the upper forcing block in the two experiments above and one experiment at right. Berea has a relatively high permeability of $\approx 10^{-13}\,m^2$, whereas the permeability of Westerly granite is in the range 10^{-20}–$10^{-19}\,m^2$. When the two experiments at right that used Westerly as the upper forcing block were disassembled after the tests, the gouge was still dry even though the top of the granite piece was wet. Fluid pressure had been applied to the two samples several hours before the experiments were run. The 125°C sample has the same strength as the dry sample above. The one dried at 50°C is somewhat weaker, consistent with the incomplete removal of adsorbed water from the gouge.

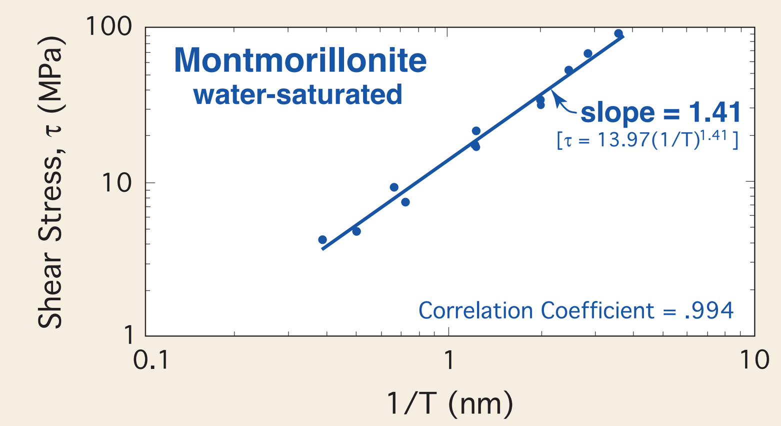


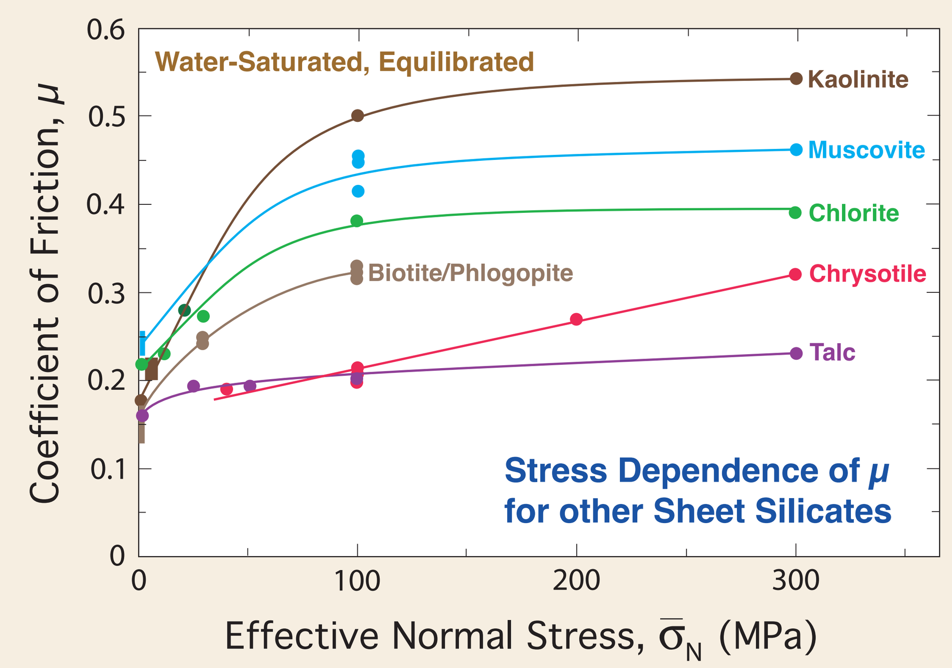
Water-Saturated, Equilibrated Strengths: Effect of $\bar{\sigma}_N$











To sort out the data on montmorillonite, we first identified those experiments using deionized water-saturated samples that are considered to have maintained equilibrated fluid pressures during the tests. As illustrated above (center), μ increases rapidly with increasing effective normal stress at low stress levels and then more slowly at higher stresses. The spread of μ at a given effective normal stress reflects differences in experimental conditions such as sliding velocity and the amount of displacement. Israelachvili et al. (1988) determined experimentally that the shear strength of a water film between two mica plates increases as the number of water layers in the film decreases. This inverse relationship between water film thickness and shear strength at a given effective normal stress is illustrated above (right), using water film thicknesses calculated by Renard and Ortoleva (1997) from Debye-Hückel/osmotic theory, assuming a surface charge energy of -0.01 C/m^2 at room temperature.

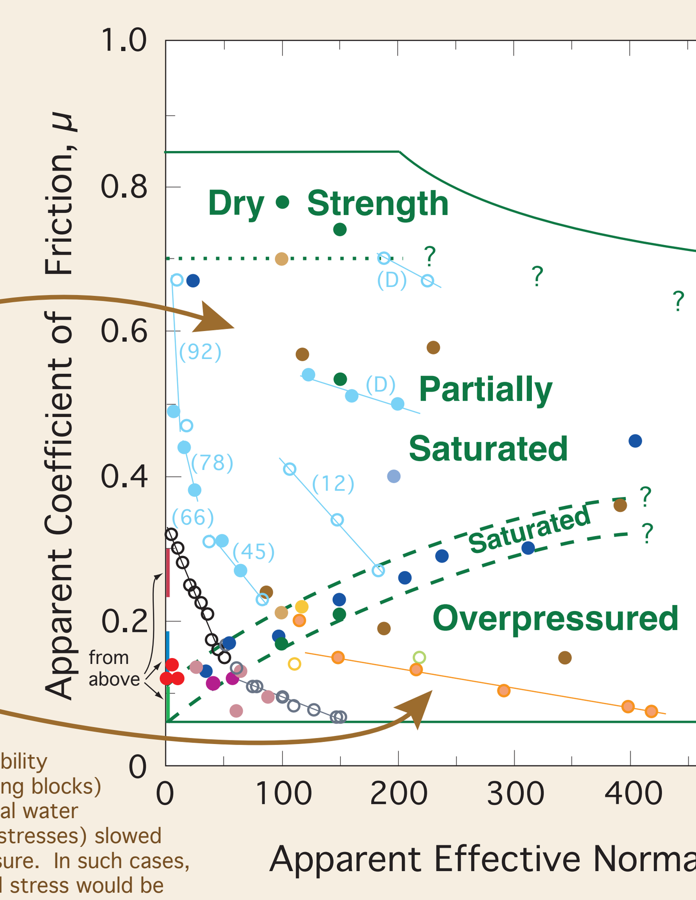
This behavior relative to effective normal stress contrasts to that of common rock-forming minerals such as quartz and feldspar, for which μ decreases at effective normal stresses above 200 MPa. Our data combined with those of Horn and Deere (1962), Kenney (1967), Brown et al. (2003), and Bos and Spiers (2000) suggest that μ also increases with effective normal stress for many other sheet silicates under saturated conditions, as illustrated at left.

Soil mechanics investigations (above left) show that μ increases with increasing salinity. Saline pore fluids will tend to collapse the double layers of water on the montmorillonite grains which, in turn, will increase shear strength. A saturated NaCl solution raises μ 4-fold at these low normal stresses, the equivalent of increasing effective normal stress to ≈250–300 MPa for montmorillonite gouge saturated with deionized water.

Interpretation of Montmorillonite Strength Data

Many of the montmorillonite friction experiments reported in the rock mechanics literature used "room-dry" samples that contained several weight percent adsorbed water and that were, in consequence, weaker than thoroughly dried montmorillonite. Increasing normal stress will reduce porosity of the gouge and bring such samples closer to saturation.

In several other tests, the experimental design (e.g., use of Westerly granite or equally low-permeability Tennessee sandstone as forcing blocks) and conditions (e.g., high initial water contents and/or high normal stresses) slowed the equilibration of fluid pressure. In such cases, the apparent effective normal stress would be higher than the true value and μ calculated using the "apparent" stress would be lower than the true value, as first suggested by Wang et al. (1980).



Legend

- filled symbols: Na-montmorillonite
- open symbols: Ca-montmorillonite
- This study
- Morrow et al. (2000)
- Morrow et al. (1992)
- Bird (1984) () = % humidity, D = dry
- Saffer et al. (2001)
- Summers and Byerlee (1977)
- Wang et al. (1980)
- Saffer and Marone (2003)
- Logan and Rauenzahn (1987)
- Morrow et al. (1982)
- Shimamoto and Logan (1981)
- Brown et al. (2003) [seawater]
- Lockner and Tanaka, in prep.

The data set of montmorillonite strengths is replotted here with the field of (deionized) water-saturated, equilibrated strengths from above (labelled "Saturated") superimposed on it. Another field labelled "Dry Strength" is defined by our experiments on thoroughly dried montmorillonite gouge. Byerlee (1978) found that for most rock-forming minerals other than the sheet silicates, $\mu \approx 0.85$ at normal stresses ≤200 MPa and μ decreases somewhat at higher stresses. This trend, known as Byerlee's law, should provide the upper limit for dry montmorillonite strength.

Those data that plot between the dry and water-saturated fields are interpreted to represent a "Partially Saturated" state in which the operative friction mechanisms may be a mixture of those characteristic of dry and water-saturated gouge. Those data plotting between the saturated field and the μ = 0.06 line may have developed fluid overpressures ("Overpressured") that were not alleviated over the duration of the experiments.