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LABORATORY MEASUREMENTS OF FREQUENCY DEPENDENT MODULI AND ATTENUATION FOR CLAY AND CLAY-BEARING SEDIMENTARY ROCKS FROM 2 TO 200 HZ

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ABSTRACT

Frequency dependent elastic properties and time-dependent mechanics of clay and clay bearing sedimentary rocks are significant for a variety of geophysical and geotechnical problems. We focus here on questions arising from observations of the variability of ground motion at different sites that occur during earthquakes. We first describe laboratory experiments undertaken to understand the effect of rock properties on site variability for friable, soft rocks collected in Southern California. A mechanical oscillator, capable of reproducing seismic frequencies in shear (torsional geometry), is used to test these friable sandstones at atmospheric pressure under dry argon or 100% relative humidity conditions. Results indicate that large variances in shear modulus and attenuation can occur for soft rocks that appear to be superficially similar. Shear moduli determined at low frequencies, 2 to 10 Hz, depend on water vapor adsorbed at grain contacts. Reductions of ~40% can occur when particular rocks are exposed to 100% rh vapor. Water sensitivity is associated with the presence of smectite that can comprise as much as 20% of the rock by volume as determined by x-ray diffraction. Other samples show very little water sensitivity. These rocks are similar to the first set, but appear to be cemented by gypsum instead of smectite. Smectites have the property of accommodating water between the aluminosilicate sheets making up the crystallites, producing swelling pressure with hydration. Gypsum cement does not swell and produces much less low frequency weakening with hydration.

In order to investigate these phenomena directly, we measured the mechanical response of smectites with depth-sensing nanoindentation augmented with force oscillation operating from near DC to 200 Hz. At ambient temperature, the number of water layers intercalated in smectites can be controlled between 0 and 4 depending on relative humidity. Suspensions of smectites (Crook Co, WY and Belle Fourche, MT montmorillonites) were dried on optically flat fused silica substrates to create thin films in which the 1 nm sheets are predominantly oriented parallel to the substrate. The static Young's modulus decreased from ~11 GPa to between 3 and 5 GPa for samples tested in dry nitrogen and 30 % RH air, respectively. The character of the force penetration curves changed, indicating local softening (possibly cracking or a pressure driven phase transition) in the dry nitrogen case and nearly ideal viscoelastic response in humid air.

Force modulation experiments, which produce displacements of ~ 100 A, show frequency dependent modulus and damping for both conditions, but effects are stronger in the more hydrated materials. The tangent of the phase angle between the applied force and resulting displacement is a direct measure of the mechanical damping (Q^{-1}) of the material. The loss tangent of the nominally dry sample increases to ~0.2 at 100 Hz, peaks and then shows indications of decreasing. This is large damping, amounting to 20% loss per loading cycle. The humidified sample displays a loss tangent of nearly 0.4 at 150 Hz before peaking. Both data sets show classical viscoelastic response, with no clear indication of amplitude dependence.

The dramatic reduction in modulus that occurs when water is introduced into montmorillonite is consistent with a reduction in bonding between the silicate layers that make up the anhydrous structure. Karaborni et al., 1996 used a hybrid molecular dynamics-Monte Carlo method to simulate the hydration of montmorillonite. In the course of the simulation, two distinct configurations for the bound water were favored as a function of separation. At 9.7 and 15.5 A, some molecular water favored sites in hexagonal micro cavities in the silicate layers. At other separations, 12 and 18.3 A, no water was embedded in the structure, but instead the water protons formed hydrogen bonds at the silicate layer surfaces. Sodium ions also favored different positions relative to the water molecules for these two cases. These changes in the configuration bound water suggest a possible mechanism for the strong damping displayed by montmorillonite since displacements in the experiments are sufficient to change the interlayer

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spacing forcing water molecules and/or sodium ions to move between the preferred sites as hypothesized by the simulations. Motions of water at the molecular scale thus may provide an explanation for the dramatic changes in mechanical response smectite bearing sandstones associated with high humidity.

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