Effect of humidity and interlayer cation on frictional strength of montmorillonite

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Smectite has been ubiquitously seen in fault gouge [Ohtani et al., 2000; Schleicher et al., 2006; Kameda et al., 2015] and is characteristic by low frictional coefficient [Summers and Byerlee, 1977; Shimamoto and Logan, 1981]; consequently, it has a key role in fault dynamics [Ikari et al., 2007; Ujiie et al., 2013]. The water content of montmorillonite decreases with increasing depth corresponding to temperature and pressure [Bird, 1984]. And the interlayer cation species of montmorillonite change corresponding to depth [Kameda et al., 2016]. Thus, to more understand fault dynamics, it is necessary to study the effect of hydration on the frictional strength of montmorillonite, which have various interlayer cation spices. However, experimental study for frictional strengths of cation-exchanged montmorillonite under controlled hydration state has rarely reported. Because it is known that the water content of montmorillonite increases with relative humidity, we developed the humidity control system in biaxial friction testing machine and investigated the effect of relative humidity (hydration state) and interlayer cation on frictional strength of montmorillonite. The humidity control system consists of two units, the sample holder (pressure vessel) unit and the vapor generating unit. We controlled both the core holder temperature and the vapor temperature independently, thereby controlled relative humidity. The frictional experiments in this study were performed at five different relative humidity (RH) conditions (10, 30, 50, 70, and 90 %). Na-montmorillonite and Ca-montmorillonite (cation exchanged from Na-montmorillonite with $CaCl_2$ solution) were sheared in this study. In all experiments, the samples were applied normal stress during sliding was kept constant at 10 MPa and sheared at 3 μm/s, and the core holder temperature was kept constant at 95 °C. The results of frictional coefficients for both Na- and Ca-montmorillonite decrease with increasing RH. The frictional coefficient of Na-montmorillonite decrease from 0.33 at RH 10 % to 0.062 at RH 90 % and the frictional coefficient of Ca-montmorillonite decrease from 0.25 at RH 10 % to 0.037 at RH 90 %. The frictional coefficients of Na-montmorillonite are larger, compared to Ca-montmorillonite at same RH conditions, which is consistent with Behnsen and Faulkner [2013] using water saturated samples. This trend can be explained by difference of hydration energy, that is, the smaller hydration energy leads closer interlayer distance and stronger bonding between silicate layers [Behnsen and Faulkner, 2013]. There is a negative correlation between water content and frictional strength, which is consistent with previous research [Bird, 1984; Ikari et al., 2007]. For explain the decrease of frictional coefficient with increasing relative humidity, there are two main water weakening mechanisms; (1) the shear strength weakens due to hydration of interlayers and expands distance between layers in montmorillonite [Bird, 1984], (2) the shear strength decrease due to water-film on the particles become thick [Moore and Lockner, 2007]. The changes of interlayer distance with interlayer swelling corresponding to relative humidity are discontinuous at atmospheric pressure [Morodome and Kawamura, 2009], whereas water content of montmorillonite increases continuously with increasing relative humidity [Xu et al., 2000]. From our results that frictional strength decrease continuously with increasing relative humidity, the negative correlation between frictional strength and relative humidity can be explained by mainly interparticle swelling. Our results show hydration state and interlayer cation species are particularly germane to frictional strength. For considering frictional strength at deep underground, an important point to emphasize is that Na-montmorillonite is stronger than Ca-montmorillonite not only at saturated with water [Behnsen and Faulkner, 2013] but also dry state.

Keywords: montmorillonite, hydration, humidity, interlayer cation, frictional strength

