Viscoelastic damage model for rate-dependent shear behavior of shales

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Shales are the most ubiquitous material on the earth's surface. Improved understanding of the mechanical behavior of shales is one of the important challenges in the geomechanics community, as shales are often encountered in many energy and environmental engineering applications. The strain rate-dependent mechanical behavior of shale was extensively characterized using triaxial compression tests carried out at different loading rates. A constitutive model for shale under high confining pressure and different strain rates was proposed based on the experimental results. The model is based on a combination of viscoelasticity and damage mechanics, such as the model developed by Katsuki and Gutierrez for asphalt concrete. The model is formulated to predict the quasi-brittle behavior of shales in the pre-peak stage and the strain softening post-peak behavior. The post-peak response is believed to be caused by the growth of microcracks in shales de-bonding and de-cohesion mechanisms responsible for the microcrack evolution. The combined laboratory testing and modeling showed that higher axial loading strain rates lead to higher elastic modulus and higher peak shear strength, with both following exponential function relationships with axial strain rate. Failure results in a single linear shear fracture when the axial strain rate is less than $10^{-5}\ 1/s$. In contrast, when the axial strain exceeds $10^{-5}\ 1/s$, more complex development of multiple micro-cracks occurs, forming a crisscrossing fracture network. Failure in shale can be described by a damage variable D which is slightly larger than zero in the compaction stage and is almost zero in the elastic phase, gradually decreases when the load reaches the yield stress, then reduces to a minimum after the yield stress. Taking the yield stress as the cut-off point for damage and considering the evolution of the shale damage variable, a new measure of micro-mechanical strength F is proposed. Based on Lemaitre's equivalent strain assumption and the new variable F, a statistical strain-rate dependent damage constitutive model for shale is established with physically meaningful model parameters. The model predictions are compared with the results of an extensive series of triaxial tests on shale shear behavior under different shearing rates. The excellent agreement between the model predictions and experimental data demonstrates the validity and reliability of the proposed model formulation.