PREDICTION OF TIME AND ENVIRONMENT-DEPENDENT STRENGTH: FRACTURE MECHANICS APPLIED TO CRUSTAL ROCKS, Peter L. Swanson and Hartmut Spetzler, Cooperative Institute for Environmental Sciences and Department of Geological Sciences, University of Colorado, Boulder, CO 80309

In order to predict the strength of rock over time periods appropriate to planetary tectonics it is necessary to account for the degradation of material strength by the available liquid or gaseous species in the surrounding environment [1,2,3]. The distribution of the (mostly) volatile corrosive elements during the formation of the solar system allows for the possibility of widely varying time-dependent strengths of mineralogically similar rocks. It is therefore necessary to consider such an effect when trying to interpret the history of solar system bodies based on surface morphological features. This paper describes recent efforts to obtain the necessary fracture mechanics data on igneous rocks that are used to model rock failure [4] under conditions appropriate to planetary crusts.

Experimental techniques to study the effects of time, environment, temperature, pressure and strain rate on the strength of rocks have in the past been primarily simple compression tests. The failure process begins with the creation and then extension of tensile microcracks oriented near parallel to the direction of maximum applied deviatoric stress and ends with the coalescence of these tensile features in a macroscopic shear fracture. To account for the macroscopic time-dependent strength it is necessary to understand how the growth of tensile microfractures depends on the experimental variables. This information is obtained from "single crack" or fracture mechanics experiments in which flat plates of rock are "split" or "halved" with fracture velocities ranging from $\sim 10^{-2}$m/s to $\sim 10^{-9}$m/s [5,6]. Crack velocity, v - stress intensity factor, $K_I$ diagrams are used to display and compare results obtained under different environmental conditions. The form $v \propto K_I^n$ is found to be a good empirical fit where n is known as the stress corrosion index and is a controlling parameter in the time-to-failure under conditions of constant stress or the strength during constant strain rate conditions. From calculations of the time required for a crack to grow to its critical Griffith length it is easy to show [7] the relationship between the stress corrosion index, n, and the times-to-failure at different constant applied (creep) stresses, $\sigma$,

$$\left(\frac{\sigma_i}{\sigma_j}\right)^n = \frac{t_j}{t_i} \tag{1}$$

and the failure strengths at different constant strain rates, $\dot{\varepsilon}$,

$$\left(\frac{\sigma_i}{\sigma_j}\right)^{n+1} = \frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_j}. \tag{2}$$

Simple materials such as glass and some fine-grained ceramics [8] show agreement between n-values obtained in these three different experiments.

In structurally more complex materials there is not always good agreement [8]. A comparison of the time-dependent deformation associated with the addition of a $H_2O$ droplet to the "elastic" portions of double torsion specimens of glass and granite is illustrated in the double exposure holograms pictured in Figure 1. Both specimens are undergoing macroscopic subcritical fracture at $\sim 10^{-9}$m/s from left to right and the holography shows the complicated behavior observed in a complex material like granite. The time-dependent response is likely to be composed of stress corrosion controlled extension of naturally occurring microcracks, environment enhanced asperity indentation between grain contacts and capillary pore pressure and adsorption effects. Such complex time dependent behavior in the presence of moisture is inherent in the fracture propagation process in rocks and adds to the difficulty in defining the $K_I$-v relation. Variability in the $K_I$-v relation or n-value leads to errors in estimates of times-to-failure [9] that are critical when extrapolating to times pertinent to large scale planetary processes. For instance, if we wish to establish a time-to-failure of 1 billion years to within a factor of 2, we need to determine the stress corrosion index to better than a very few percent. Such precision is rarely attained in the simplest of synthetic materials. Even if such precision was possible for complex materials, extrapolations over long periods of time are not useful unless the environmental history is also known. These calculations

can, however, when considering the environment, assist in determining the relative lifetimes and subcritical fracture resistance of planetary crustal materials.

n-values for 5 rock types and glass microscope slides were measured by the relaxation mode of double torsion testing [5,6] at 20°C, 40% relative humidity and are summarized in table I. The large scatter in n-values observed for rocks is produced in part by microstructural heterogeneities such as microcracks, pores, residual stresses, grain boundaries, and elastic mismatches associated with a multiphase material, etc., and partly by the experimental technique. The relaxation form of double torsion testing is a transient method and does not measure crack velocities with the fracture in equilibrium with the environment. This leads to an apparent non-unique relationship between the crack velocity and the stress intensity factor. Operating under constant load or loading rate rather than fixed displacement should produce constant crack velocities in a state of equilibrium with the environment. Even though the scatter is large, the $K_I$-v relations for these materials are characteristic enough to establish significant differences between them.

Before accepting the notion that basaltic rock-types have a greater resistance to subcritical fracture than the granite or shale (under these particular environmental conditions), it is first necessary to confirm these n-values using an independent technique. In an attempt to make such a confirmation on ceramics and a limestone, Lankford [10] examined n-values determined by using the relation (2) with results from compression tests. Although there is undoubtedly some relation between n-values obtained in fracture mechanics experiments and the strain rate dependent compressive strength, we feel that a crack interaction model is necessary to describe the time and environment-dependent strength of rock.

References

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| Material Type | No. of Tests | Mean and Standard Deviation of n | Standard Deviation as % of n |
|---|---|---|---|
| glass | 6 | 18.7±1.8 | 10 |
| Tholeiitic basalt | 7 | 170±50 | 30 |
| Devonian shale | 11 | 80±20 | 20 |
| Dresser basalt | 9 | 170±60 | 35 |
| Westerly granite | 13 | 70±25 | 35 |
| Ralston basalt | 12 | 100±20 | 20 |