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THE EFFECT OF PORE PRESSURE AND HEATING TIME ON THE STRENGTH AND SLIDING STABILITY OF A SERPENTINITE GOUGE

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ABSTRACT

The strength of a natural serpentinite gouge was measured at 400°C and an effective pressure of 100 MPa. The strength of the gouge decreased with increasing pore pressure to 50 MPa and then was nearly constant between 50 and 125 MPa. The samples at 50-125 MPa pore pressure slid stably, whereas those at 3-25 MPa pore pressure showed stick-slip behavior. Lengthening the pre-heating time to 72,000 s of samples at 100 MPa pore pressure led to increases in both the strength and the likelihood of sliding unstably. With still longer pre-heating times, the strengths decreased again and sliding once more became stable. The strength of the gouge at 3 MPa pore pressure was unaffected by changes in pre-heating time. A possible explanation for the results is that excess pore pressures are being generated in the gouge, causing the true effective pressure to be lower than the apparent value.

INTRODUCTION

An understanding of the behavior of gouge materials at depth in fault zones may be critical to earthquake prediction. Moore et al. (1983) described the effects of temperature and confining pressure at 3 MPa pore pressure on the strength and sliding stability of three sheet-silicate-rich gouges and a gouge composed of crushed Westerly granite. Similar studies at 100 MPa pore pressure have recently been completed (Moore et al., in preparation). Comparison of these results showed that at 400° and 600°C the sheet-silicate-rich gouges were considerably stronger at 3 MPa pore pressure and 100 MPa confining pressure than at 100 MPa pore pressure and 200 MPa confining pressure. Because the imposed effective pressures in these experiments were nearly the same, the marked differences in strength suggested that the effective stress law might not hold at high temperatures. The experiments described in this paper test the effects on gouge strength of changing pore pressure at a constant effective pressure and temperature, using the serpentinite gouge of previous studies. Additional experiments test the importance of heating time on gouge strength. These results also apparently contradict the effective stress law; however, we propose that this law does hold and present a theory in which excess pore pressures generated at different times in the gouge layer reduce the true effective pressures. This theory will be tested in future experiments.

EXPERIMENTAL PROCEDURES

The serpentinite gouge material used is a natural gouge collected from the San Andreas fault zone near San Carlos, California. The gouge consists essentially of chrysotile, with trace amounts of calcite, chlorite, and an opaque mineral. The experimental assembly is described in detail in Moore et al. (1983). Each sample consisted of a 0.65-mm-thick layer of gouge sandwiched between 30° polished sawcut surfaces in a 19-mm-diameter granite cylinder. Heat was provided to the sample by a surrounding resistance heater, and the deionized water that served as pore fluid was introduced to the sample through a hole drilled into the upper granite piece. Pressures and strains were computer-controlled and -recorded; force and displacement measurements were made outside the pressure vessel using a load cell and displacement transducer. After pore and confining pressures were applied, the samples were heated and then held at temperature and pressure for a specified period of time before loading. All experiments were run at 400°C, an effective pressure of 100 MPa, and an axial shortening rate of 4.1×10^{-3} mm/sec. In one set of experiments, the effect of changing pore pressure to 125 MPa was investigated, with the samples held at 400°C for 1,800 s prior to loading. In a second set, the samples at 3 and 100 MPa pore pressure were held at 400°C for periods of time up to 172,800 s before loading.

RESULTS

The results of the experiments at varying pore and confining pressures are shown in Figs. 1 and 2. Also included are results at 3 MPa pore pressure and 100 MPa confining pressure from Moore et al. (1983), which yield strengths consistent with the other results. As shown in the figures, the strength of the serpentinite gouge decreases systematically with increasing pore pressure to about 50 MPa; above that value, the measured strengths do not differ significantly from each other. After 1.5 mm displacement, the samples at 3 MPa pore pressure support differential stresses of about 280 MPa, whereas those at 50 MPa or greater pore pressure support only about half that amount of stress. The occurrence of stick-slip

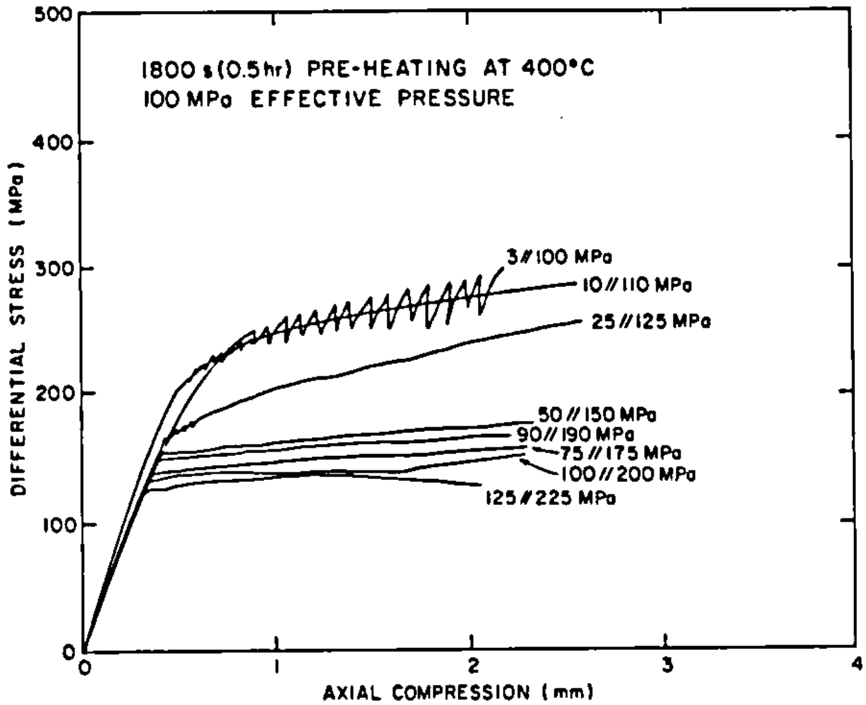

Fig. 1. Plot of differential stress against axial compression for sliding experiments on serpentinite gouge held at 400°C for 1800 s (0.5 hr), at 100 MPa effective stress and 10^{-4}/s strain rate. Labels on the curves indicate pore and confining pressure, respectively.

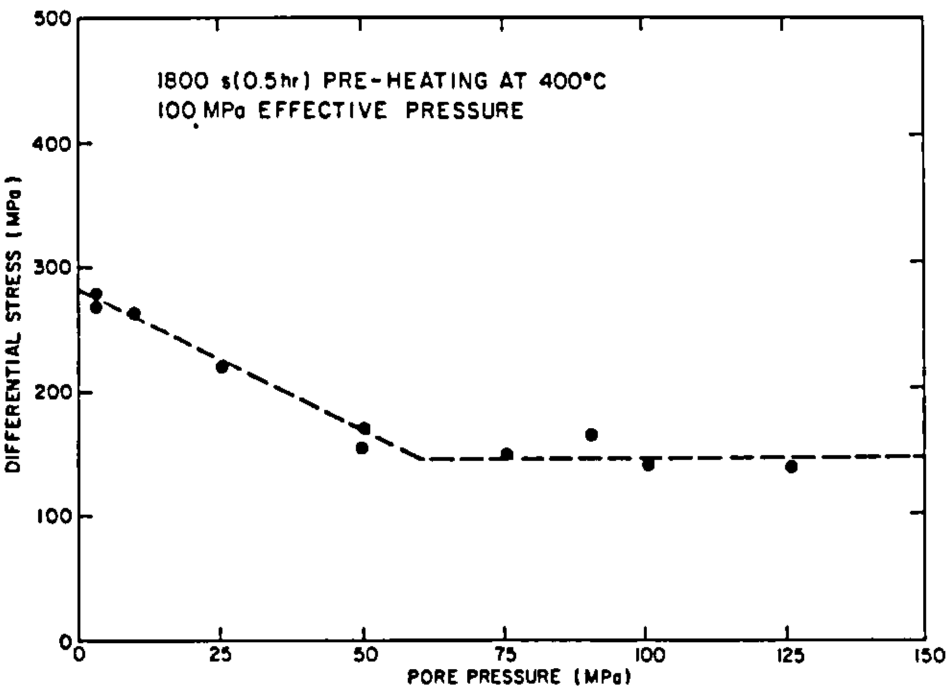

Fig. 2. Differential stress after 1.5 mm sliding for each of the experiments in Fig. 1, plotted with respect to pore pressure.

also is a function of pore pressure. The samples at 3 MPa pore pressure showed pronounced stick-slip, those at 10 and 25 MPa pore pressure initially slid unstably, and those at 50-125 MPa pore pressure slid stably (Fig. 1). X-ray diffraction analysis of the samples indicated that no new mineral phases had grown and no significant changes in peak intensities had occurred. The results of the experiments varying the pre-heating time at 400°C are shown in Figs. 3-5. For times to 72,000 s, the serpentinite gouge at 100 MPa pore pressure shows a general increase in strength to a value roughly equal to that of the 3 MPa sample in Fig. 1. The samples pre-heated for 57,600 s and 72,000 s also slid unstably. For pre-heating times beyond 72,000 s the gouge at 100 MPa pore pressure shows a decrease in strength and a return to stable sliding. X-ray diffraction analysis of the run products showed no change in mineralogy with increased heating time. At 3 MPa pore pressure the gouge shows no change in strength or sliding behavior with an increase in heating time to 126,000 s (Fig. 5).

DISCUSSION

Numerous studies have shown that when a pore fluid is introduced to soil or rock samples, their deformation behavior becomes a function of effective stress or effective pressure (see Brace, 1972, for review). In particular, Byerlee (1967) demonstrated that frictional sliding along sawcut surfaces of Westerly granite at room temperature was consistent with effective stress theory. Byerlee and Brace (1972) also found that the onset of stick-slip in room-temperature sliding experiments on gabbro was a function of effective pressure.

The experimental results summarized in Figs. 1 and 2 of this study seem to indicate that the effective stress law does not hold at 400°C, because frictional strength decreased with increasing pore and confining pressure at a constant effective pressure. An increase in heating time over a short span (16-20 hr) removes the strength differences between samples at high and low pore pressures (Figs. 3, 5). However, for still longer times the strength differences reappear. In addition, in contrast to Byerlee and Brace's (1972) results, the sliding motion is not a simple function of the apparent effective pressure. Instead, the gouge samples showing stick-slip are the ones with the highest measured strengths.

The results of these experiments can be explained in one of two ways. First, the effective stress law may be invalid for some gouge materials at high temperatures. Alternatively, the effective stress law may be valid, but by some means the effective pressure felt by the gouge differs from what is externally applied. The results from previous studies at 3 and 100 MPa pore pressure and approximately 100 MPa effective pressure (Moore et al., 1983; in preparation) are pertinent to this discussion. In these experiments, both the sheet-silicate-rich gouges at 200°C and the granite gouge at all temperatures studied obeyed the effective stress law. Differences in

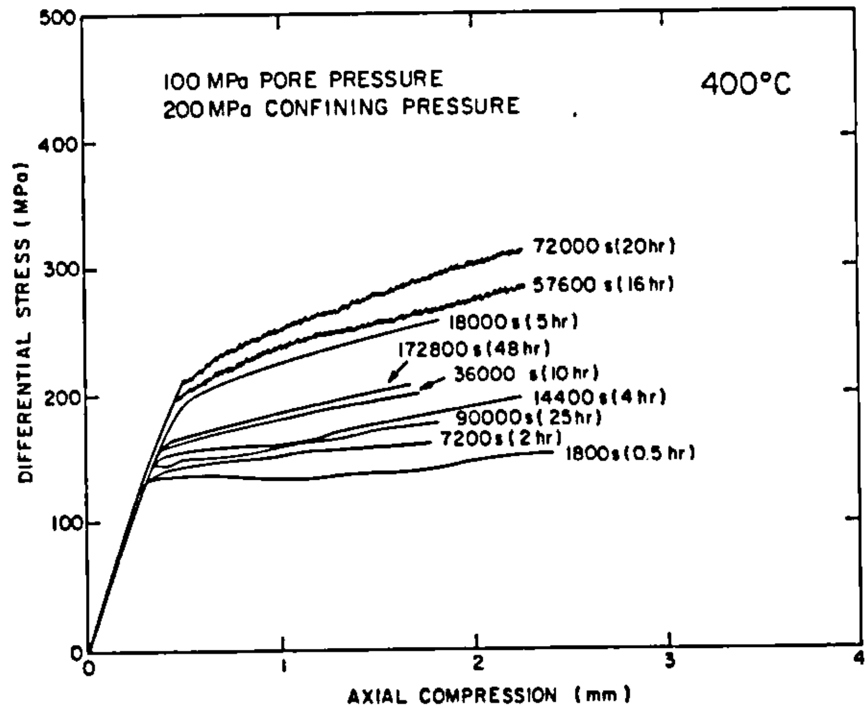

Fig. 3. Results of friction experiments on serpentinite for different heating times at 400°C, 100 MPa pore pressure, 200 MPa confining pressure, 10^{-4}/s strain rate.

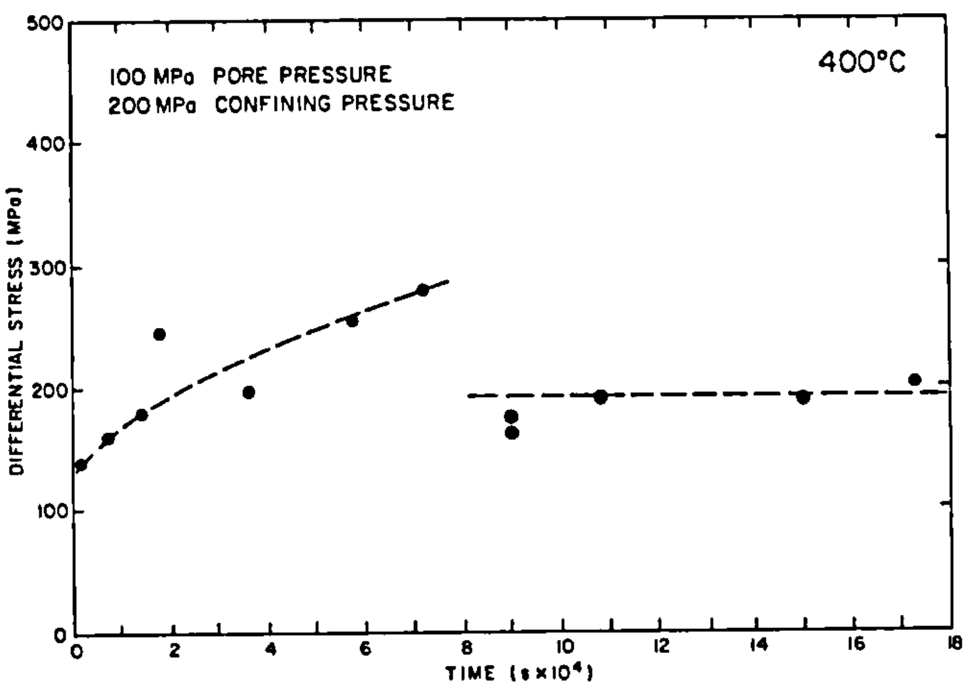

Fig. 4. Differential stress after 1.5 mm sliding for the experiments in Fig. 3, plotted with respect to pre-heating time at 400°C. Results at 108,000 s and 149,400 s are not shown in Fig. 3 due to lack of space.

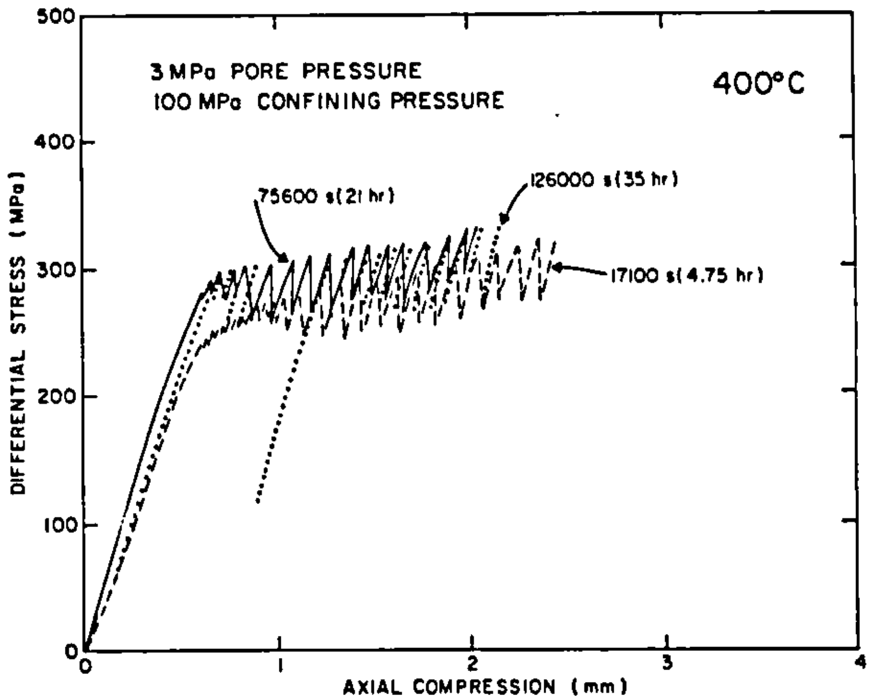

Fig. 5. Plot of differential stress versus axial compression for different heating times at 400°C.

strength at similar effective pressures were measured only at 400°C and 600°C for the sheet-silicate-rich gouges.

Because strength measurements for the granite gouge indicated the validity of the effective stress law at 400°C, the present inconsistent results with serpentinite gouge must be related to the gouge material used rather than to an equipment problem or the fact that the temperature was above the critical temperature of water (about 374°C). The changing strengths with increasing pore pressure and heating time also cannot be related to changes in the mineralogy of the serpentinite gouge because no mineralogical differences were found among the samples analyzed by x-ray diffraction. Some textural differences do exist between the sheet silicate gouges at 400°-600°C that apparently do not obey the effective stress law and the granite and 200°C sheet silicate gouges that do. At the end of an experiment, the granite and low-temperature sheet-silicate-rich gouges remained loose, granular aggregates similar to the starting material, whereas the other gouge samples had become harder and denser. This hardening of the serpentinite gouge may help explain the observed relationship between pore pressure and strength. Pore pressures were applied to the samples prior to heating in all the experiments. Given the limited pore space available, an increase in temperature will cause local overpressurization of the fluid. This excess pressure developed upon heating is relieved with time as fluids are vented back through the granite to the pore pressure inlet. The amount of time required for the fluids in the heated gouge to return to the externally imposed pore pressures will vary inversely with the permeability of the gouge.

The initial permeability of the granite gouge is relatively high because it is composed of strong, sub-spherical grains. This gouge remains granular and loose with heating; as a result, its permeability is not reduced and excess pore pressures are quickly dissipated. The initial permeabilities of the sheet-silicate-rich gouges also are apparently not low enough to cause a short-term pressure increase of pore waters heated to 200°C. However, the increase in pore pressure with heating will be much greater at 400°C than at 200°C, while the permeability of the hardened, dense gouge at 400°C will be much lower. The combination of high temperatures and very low permeability in the serpentinite gouge creates the potential for temporary strength reductions caused by pore pressure build-up. Given these conditions, the initial pore and confining pressures will control the amount of decrease in effective pressure and therefore of strength upon heating. For example, at starting pore and confining pressures of 3 and 100 MPa, respectively, a subsequent 50 percent increase in pore pressure causes only a small change in the effective pressure. At 100 MPa pore and 200 MPa confining pressure, a 50 percent increase in pore pressure reduces the effective pressure by half. This relationship is seen in Figs. 1 and 2, where the strength decreases of the gouges at low pore pressures are smaller than those at high pore pressures. The leveling off of strengths at pore pressures above 50 MPa may represent the limit of excess pore pressurization upon heating to 400°C. As the amount of pre-heating time is increased (Figs. 3, 4), the excess pore pressures in the gouge gradually equalize with the externally controlled pore pressure, and the strength of the gouge is the same at high and low fluid pressures.

The temporary change in pore pressure with heating explains the behavior of the serpentinite gouge at high fluid pressures to its point of maximum strength (Figs. 3, 4). If this effect were the only one operating on the gouge, its strength should level off at the high value attained after approximately 72,000 s. The reweakening of the gouge at still longer times must therefore have some other cause. A possible explanation for this effect may be found by considering the granite cylinders that house the gouge layers. To prevent the loss of gouge material, the pore pressure inlet does not extend completely to the gouge; instead, fluid must flow a short distance through granite. Because of this, any changes in the permeability of the granite during the experiment can affect the pore pressure and ultimately the strength of the gouge. Summers et al. (1978) achieved significant permeability decreases in Westerly granite at 400°C by flowing water down a pore pressure gradient. Flow completely stopped within 2 days of the start of five out of six of their experiments. The permeability reductions were attributed to dissolution of silicate minerals on the high pressure side of the granite and their redeposition on the low pressure side, which sealed off cracks and pore spaces. In a similar way, the movement of pore fluids through the Westerly granite cylinders surrounding the serpentinite gouge may cause a reduction in their permeability. If the granite permeability becomes sufficiently low, the pore fluids in the gouge will in effect be cut off from the pore pressure inlet. From that time on, any excess pore pressures in the gouge can no longer be dissipated. The time at which the second weakening of the serpentinite gouge sets in is comparable to the amount of time needed to halt flow in the 400°C experiments of Summers et al. (1978). This is a longer time than is needed to completely remove the excess pore pressures developed upon initial heating (Fig. 3). However, an additional fluid pressure increase may accompany the application of the differential stress. This effect may be small compared to the temperature effect and therefore go unnoticed in the short-term experiments. However, this pressure increase may be sufficiently high to weaken the gouge if the initial pore pressure is high and if no pore fluids at all can flow into the granite. Again, the strength of a gouge at an initially low pore pressure will be little affected by the sealing of the granite cylinder, as illustrated by the long-term experiment in Fig. 5.

In summary, this interpretation of our results suggests that the effective stress law is still be valid at high temperatures. Our seemingly contradictory data can be explained by the operation of various factors that raise the pore pressure in the gouge to values higher than the externally imposed pore pressure. As a result, the true effective pressure during the runs is often lower than the apparent value. It must be emphasized that this explanation of the data is at present only a hypothesis. However, because of the importance of these results to interpreting fault behavior, much further work is planned to test this theory.

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