ABSTRACT:

Thermal expansion measurements were conducted as a function of confining pressure on welded specimens of Topopah Spring Member tuff recovered from borehole USW SD-12 at Yucca Mountain, NV. Each specimen was tested at confining pressures between 1 and 30 MPa over a nominal temperature range of 25 to 250 °C. On several specimens, the higher confining pressure thermal cycles were performed first to inhibit thermal effects, such as cracking, that occur at lower confining pressures in other rock types.

The coefficient of thermal expansion for welded tuff increases with temperature. At temperatures below 100 °C the mean coefficient of thermal expansion range from 7.7 to 10.8 x 10^{-6} °C^{-1}. As temperatures approach 250 °C, the thermal expansions increase markedly to values of 14.2 to 20.6 x 10^{-6} °C^{-1}. The effect of confining pressure on thermal expansion for tuff is small.

INTRODUCTION

An integral part of the licensing procedure for the potential nuclear waste repository at Yucca Mountain, Nevada involves the prediction of in situ characteristics of the tuff for the emplacement of radioactive waste containers. The data used in modeling the thermal and mechanical behavior of the repository rock require a detailed knowledge of the rock properties. In particular, the thermal expansion, thermal conductivity, heat capacity, elastic constants and strength as a function of porosity, temperature, and pressure for the welded tuff in the proposed repository horizon are required.

Previous studies show that thermal expansion of low porosity, crystalline rocks depends not only on temperature, but also confining pressure. Wong and Brace, (1979) and Heard and Page (1980) report that the coefficient of thermal expansion for granite increases with temperature and decreases with confining pressure. Decreases in the mean coefficient of thermal expansion for Westerly granite of as much as 40% are observed as the confining pressure increases from 7.6 to 55.2 MPa on specimens heated to 300 °C (Wong and Brace, 1979).

Heating, even to moderate temperatures, produces damage in the form of microcracks in granites. The formation of microcracks in granite specimens during thermal cycling is due to the differential thermal expansion of quartz and feldspars along grain boundaries. The increase in microcrack porosity results in a decrease in the elastic constants and strength and an increase in permeability at low confining pressures. Summers et al. (1978) show that thermal cycling to 400 °C increases the permeability of granite specimens, presumably due to enhanced microcrack populations. Johnson et al. (1978) and Simmons and Cooper (1978) observe that thermal cycling under ambient conditions, augments the microcrack density in granites at temperatures as low as 75 °C.

In general, the porosity in granite is characterized by low aspect ratio microcracks. The porosity in the Topopah Spring member welded tuff, in contrast, is characterized by relatively large spherical to elliptical lithophysae and vapor-phase altered zones. These differences in pore geometry produce significantly different pressure dependencies for the elastic constants of tuff and granite (Haupt et al., 1992; Martin and Haupt, 1994; Price et al., 1994). The effect of pressure on thermal expansion has not been studied on tuff from the potential repository horizon. Therefore, it is important to assess the role of the pore geometry on thermal expansion under appropriate repository conditions.

In light of the fact that thermal cycling increases microcrack porosity in granite specimens, and confining pressure decreases the effects of microcracks, it is of interest to determine first whether microcrack formation occurred during the thermal expansion of welded tuff, and second to establish the role of pressure on the inhibition of microcrack development.
Thermal expansion experiments were performed on five welded tuff specimens prepared from core recovered from borehole USW SD-12 at Yucca Mountain, NV. The specimens were prepared from vertical cores by subcoring parallel to the axis. Each test specimen is a ground, right-circular cylinder 50.8 mm in diameter and 101.6 mm in length. Bulk density and compressional and shear wave velocities were measured on each of the specimens prior to and after the thermal expansion measurements. The specimens were tested room dry. The average grain density was determined with the water pycnometry technique using pieces remaining from the subcoring attendant to the preparation of the specimens.

The composition and total porosity of each tuff specimen was very similar. The specimens were all from the densely welded, devitrified, lithophysae-poor unit of the Paintbrush Tuff. Feldspars constitute the bulk of the matrix and phenocryst components, with the remainder comprised mostly of quartz polymorphs. There is low phenocryst abundance with the matrix comprising more than 90% of the specimens. The porosities range from 7.3 to 10.3%. One suite of measurements was carried out on Barre granite for comparison. This rock has a porosity of 1%, mostly in the form of low aspect ratio cracks.

The sample assembly consists of a jacketed specimen secured between two Invar endcaps. The specimen is wrapped with two layers of 0.13 mm thick, dead soft, annealed copper. The copper extends approximately 12 mm beyond each end of the specimen. The specimen is then jacketed with heat shrink teflon and secured to the endcaps using two wraps of wire. The endcaps support the cores and the barrels for two LVDTs positioned on a diametral plane through the specimen. Due to the high temperature for the thermal expansion measurements, the LVDTs are positioned at one end of the pressure vessel, away from the furnace that heats the specimen as shown in Figure 1. To minimize errors due to differential thermal expansion on the support assemblies for the LVDT cores and barrels, these items were fabricated with fused quartz tubing.

After adjusting the LVDTs, the sample assembly is placed onto the base plug of the pressure vessel. The base plug of the vessel contains ports for confining and pore pressure, four thermocouples, and high pressure feedthrus for electrical devices. A Macor insulator is secured to the base plug. The insulator provides a thermal barrier between the specimen, subjected to the high temperatures, and the LVDT cores and barrels in the low temperature portion of the vessel.

Figure 1: Schematic diagram of the pressure vessel and furnace assembly for the thermal expansion experiments.

The thermal expansion experiments, were carried out in a drained condition, at constant confining pressures of 1, 5, 10, 20, and 30 MPa over a nominal temperature range of 25 to 250 °C. The confining pressure is controlled with a servo-hydraulic intensifier which maintains the pressures constant to within ±0.15 MPa. A long bore pressure vessel was divided into a hot and a cool region.

The temperature in the hot zone is controlled with an external furnace consisting of three band heaters surrounded by insulation and protected with a stainless steel shroud. The band heaters are adjusted to produce a temperature profile constant to within ±1 °C over the test specimen at 250 °C. A programmable controller provides reproducible thermal cycles. The specimens are heated and cooled at a rate of 5.3 x 10^-3 °C s^-1. A thermal cycle consists of heating from ambient to 250 °C, and cooling to ambient conditions. A two hour hold is imposed between cycles to allow the system to equilibrate with room temperature.

The lower end of the vessel is cooled with a water jacket. The cool end of the pressure vessel houses the LVDTs sensing the displacement of the rock core during thermal expansion.

Since the fused quartz support rods for the
LVDT cores and barrels are attached to the end caps positioned at each end of the specimen; the measured displacement comprises the displacement of the tuff specimen, the end caps, the fused quartz rods, the connections, etc. To separate the total displacement from that of the specimen, a series of calibrations were performed using a fused quartz test specimen with the same nominal dimensions as the tuff specimens. It was jacketed and secured to the end caps as described above and inserted into the pressure vessel. The confining pressure is increased. The specimen is then thermally cycled and the total displacement recorded as a function of temperature. The total displacement was calculated using calibrations for the LVDTs obtained under ambient conditions. To obtain the system effect at each confining pressure, the thermal expansion of the fused quartz specimen is subtracted from the total displacement using a coefficient of thermal expansion for fused quartz of $5.5 \times 10^{-7} \, ^\circ\text{C}^{-1}$. The difference is the correction which is used to reduce the data on the test specimen.

To verify that the system, including the data acquisition system, is performing correctly, system checks are periodically performed on a specimen of AISI 446 stainless steel with the same dimensions as the tuff specimens. The system check is considered successful if the mean coefficient of thermal expansion is measured to within ± 5% of the published value over each temperature interval.

The coefficient of thermal expansion at constant pressure, $\alpha_p$, is given by:

$$\alpha_p = \left( \frac{\partial \varepsilon_a}{\partial \varepsilon} \right)_{\text{p}}$$

where $\varepsilon_a$ is the strain and $T$ is the temperature at the midpoint of the specimen. For this study, the mean coefficient of thermal expansion is calculated over 25 °C intervals. A least squares fit to the data is used to compute the coefficients. The temperature intervals are: 25-50, 51-75, 76-100, 101-125, 126-150, 151-200, 201-225, and 226-250 °C.

RESULTS

The thermal expansion as a function of temperature is similar for all five tuff specimens. Data for the initial thermal cycles at 30 MPa on a tuff specimen recovered from a depth of 236.6 m are shown in Figure 2. During the first thermal cycle, the strain as a function of temperature curve is concave upward. Upon unloading there is hysteresis; the specimen is shorter after the first thermal cycle by approximately 25 microns. The magnitude of the effect is the same whether the initial thermal cycle is carried out at 1 or 30 MPa. For the second thermal cycle, the strain versus temperature curve is also concave upward, however, there is no permanent change in specimen length at the termination of the cycle. The hysteresis during cooling is small but evident at temperatures greater than 175 °C. Subsequent experiments at the other confining pressures are nearly identical to those observed for the second thermal loading cycle at the initial pressure. The characteristics are the same for all specimens tested. Figure 3 shows a test on the same specimen at a pressure of 5 MPa.

The mean coefficients of thermal expansion computed for the first two thermal cycles of the specimen recovered for 236.6 m and tested at 30 MPa are shown in Figures 4 and 5. The data for the initial thermal cycle is given in Figure 4. The coefficient is plotted at the mid point of the interval. Open circles indicate heating, and the diamonds indicate cooling. The mean coefficients of thermal expansion at temperatures below 175 °C increases from 8.91 to 10.85 $x\,10^{-6}$ °C⁻¹. For temperatures above 175 °C, the thermal expansion increases rapidly to 17.34 $x\,10^{-6}$ °C⁻¹ between 225 and 250 °C. Upon cooling there is a pronounced hysteresis; except for the highest temperature interval, the coefficient of thermal expansion is greater during cooling than upon initial heating.

The mean coefficients of thermal expansion for the second cycle are shown in Figure 5. The values are very similar to those observed during cooling for the first cycle. The values for heating and cooling at temperatures between 25 and 175 °C show very little scatter; between 175 and 250 °C, there is hysteresis during cooling.

The effect of confining pressure on thermal expansion is small. One effect of pressure on the specimens studied is shown in Figure 6. The mean coefficients of thermal expansion computed for cooling cycles over temperature ranges 76-100 and 201-225 °C are plotted as a function of confining pressure for the specimen recovered from a depth of 236.6 m. At temperatures between 76 and 100 °C, the coefficients increase several percent as the confining pressure increases from 1 to 30 MPa. In contrast, the coefficient decreases by up to 12% over the same pressure interval for temperatures between 201 and 225 °C.

Compressibility of tuff is routinely measured during pressurization prior to each thermal expansion experiment. The data for each specimen are similar. Results of an experiment showing strain as a function of confining pressure are shown in Figure 7 for a specimen recovered from 209.6 m. The increase in strain with the pressure is nearly linear. The computed coefficient linear compressibility from these data is $1.36 \times 10^{-5}$ MPa⁻¹.

The results of a thermal expansion experiment on Barre granite at confining pressures of 1 and 30 MPa are shown in Figure 8. The data represent the second thermal cycle at each pressure. In contrast to the data for tuff, the slope of the strain versus temperature curve is only
Figure 2: Strain plotted as a function of temperature for a specimen of welded tuff recovered from a depth of 236.6 meters. The experiment was conducted at a pressure of 30 MPa.

Figure 3: Strain plotted as a function of temperature for a specimen of welded tuff recovered from a depth of 236.6 meters. The experiment was conducted at a pressure of 5 MPa.
Figure 5: Mean coefficients of thermal expansion are plotted as a function of temperature for the first thermal cycle on a specimen of welded steel recovered from a depth of 23.6 m in the experiment conducted at a continuous pressure of 30 MPa. The experiment was conducted at a cycle on a specimen of welded steel recovered from a depth of 23.6 m in the experiment conducted at a cycle on a specimen of welded steel recovered from a depth of 23.6 m in the experiment conducted at a cycle on a specimen of welded steel recovered from a depth of 23.6 m in the experiment conducted at a cycle on a specimen of welded steel recovered from a depth of 23.6 m in the experiment conducted at a cycle on a specimen of welded steel recovered from a depth of 23.6 m in the experiment conducted at a cycle on a specimen of welded steel recovered from a depth of 23.6 m in the experiment conducted at a
Figure 7: Strain is plotted as a function of pressure for a hydrotactile compression experiment on a specimen of welded unit recovered from a depth of 209.6 meters.

Figure 6: Mean coefficients of thermal expansion are plotted as a function of pressure for a specimen of welded unit recovered from a depth of 236.6 meters.
Figure 8: Strain is plotted as a function of temperature for a thermal expansion experiment on a specimen of Barre granite. The data are for the second thermal cycle at each pressure.

slightly concave upward. A greater strain is observed at 1 MPa than at 30 MPa, whereas in tuff the observed strain is nearly independent of confining pressure. Finally, the hysteresis observed during cooling is greater at 1 MPa than at 30 MPa.

At the termination of each experiment, the specimen was removed from the pressure vessel and weighed. All specimens lost mass due to thermal cycling. The loss is attributable to water driven out of the specimen due to heating. During the first thermal cycle on each specimen, steam and water were emitted at the pore pressure port at the base of the specimen assembly.

Compressional and shear wave velocities were measured prior to and after each experiment. The compressional and shear wave velocities for tuff after testing were several percent greater than those measured prior to testing. In contrast, the compressional and shear wave velocities for Barre granite shows a small decrease at the conclusion of the thermal cycling experiment.

**DISCUSSION**

The rate of change in strain with temperature increases noticeably above 150 °C. In this temperature range a polymorph of quartz, tridymite, undergoes an inversion. The increase in the mean coefficient of thermal expansion may be related to the phase change. On cooling, a small hysteresis is observed above 150 °C. Most likely the hysteresis is attributable to a reversible phase change in tridymite. Below 150 °C the heating and cooling cycles are identical after the initial thermal excursion.

The fact that the compressional and shear wave velocities in tuff exhibit an increase at the conclusion of thermal cycling suggests that no damage in the form of microcracks was done to the specimen due to thermal cycling. Furthermore, all of the specimens lost mass due to thermal cycling. The loss is attributable to water driven out of the specimen due to heating. This observation coupled with the increase in velocity suggest that the moisture driven off of the specimen may increase the surface energy in the pores and microcracks, decreasing the effective porosity, and increasing the seismic wave velocities. Regardless of the mechanism, there appears to be no significant thermal damage to the specimen due to heating to temperatures of 250 °C.

If we compare the data collected on granite to that on tuff, several significant differences are obvious. First, damage to the granite in terms of microcrack formation is apparent by the increase in velocities at the termination of the experiment. Second, the pressure dependency on the thermally induced strain is pronounced in the granite and very small in the tuff. Third, the mean coefficients of thermal expansion computed for Barre granite range from 7.5 x 10^-6 C^-1 at 50 °C to 13.5 x 10^-6 C^-1 at 225 °C. The magnitude of
the coefficient of thermal expansion and the pressure dependence are similar to that observed on Westerly granite by Wong and Brace (1978). However, the magnitude of the thermal expansion at high temperatures is much smaller than that observed in tuff at the same temperature and pressure.

The small pressure dependence on thermal expansion and the absence of microcrack formation due to thermal cycling confirms that the pore structure of the welded tuff is predominately in the form of spherical to elliptical pores. Earlier observations on the seismic wave attenuation and pressure dependence on velocity in similar specimens of the welded tuff lead to the same conclusion. Seismic wave attenuation shows a small dependency on frequency (Haupt et al., 1992) and compressional and shear wave velocities exhibit very little increase with pressure. The minimal damage exhibited by the tuff due to thermal expansion coupled with the other observations indicate that the long term degradation in rock properties due to the emplacement of the canisters will be most affected by temperature and not by microstructural changes in the rock. This fact simplifies the scaling of laboratory data to in situ conditions.

With the emplacement of the waste in the repository, the temperature around the canisters will increase and reach a peak value of 250 °C or so after one hundred years. The thermal elastic effect in the tuff will increase the in situ stress. A critical question is whether the increase in stress is sufficient to cause failure in the welded tuff designated to host the repository? Numerical models are being developed to compute the increase in in situ stress due to the age of the canisters, the density of thermal loading, and the physical properties of the tuff in the repository. While these models are pending, simple thermodynamic arguments can be used to constrain the maximum stress developed in the vicinity of the storage canisters. An upper bound on the change in pressure can be computed using the relationship:

$$\frac{\partial P}{\partial T} = \alpha \beta$$

where P is the pressure, T is temperature, \(\alpha\) is the mean linear coefficient of thermal expansion, and \(\beta\) is the linear compressibility. Assuming a mean coefficient of thermal expansion of 14 x 10^{-6} °C^{-1}, and a linear compressibility of 1.36 x 10^{-5} MPa^{-1}, the change in pressure with respect to temperature at constant volume is approximately 1 MPa °C^{-1}. Clearly, the assumption that the volume in the system remains constant is unrealistic and creates an upper bound to the calculated pressure change. These data suggest that the maximum increase in pressure in a very stiff system would approach several hundred MPa. However, the pressure of fractures, cracks, and other flaws in the repository will substantially reduce the stress developed in the vicinity of the canisters.

The stability of the repository requires the long term strength of the rock (static fatigue strength) to be significantly greater than the thermally induced stress in the vicinity of the canisters. Measurements are currently underway to determine the creep and long-term strength characteristics of welded tuff under repository conditions.

REFERENCES


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