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Thermal strain in a water-saturated limestone under hydrostatic and deviatoric stress states

Liang Pei [a,*], Guido Blöcher [a], Harald Milsch [a], Fiorenza Deon [a], Günter Zimmermann [a], Wolfram Rühaak [b], Ingo Sass [b], Ernst Huenges [a]

[a] Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Germany
[b] Institute of Applied Geosciences, Technical University Darmstadt, Schnittspahnstraße 9, D-64287 Darmstadt, Germany

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ABSTRACT

The present study is aimed at investigating the evolution of thermally induced bulk strain in a water-saturated limestone (Blaubeuren) at three different stress states. Three cylindrical rock samples are respectively loaded to a constant stress state ($\sigma_1 = \sigma_3 = 15$ MPa; $\sigma_1 = 45$ MPa, $\sigma_3 = 15$ MPa; $\sigma_1 = 75$ MPa, $\sigma_3 = 15$ MPa) at drained conditions in a conventional triaxial rock deformation apparatus before the sample temperature is cycled between 30 °C and defined levels up to 120 °C. Strain measurements are performed by one circumferential and two axial extensometers. Irreversible strain in both the lateral and axial sample directions are measured after each temperature cycle indicating permanent increases in diameter and in length. The measured bulk strain is separated into different strain components related to (1) initial stress loading, (2) reversible thermal expansion and contraction of rock matrix, and (3) some residual strain. The magnitudes of the residual strain increase with increasing deviatoric stress ($\sigma_1 - \sigma_3$) in the lateral direction but decrease with increasing deviatoric stress in the axial direction. The derived matrix thermal expansion coefficients range from 6×10^{-6} °C^{-1} to 1.8×10^{-5} °C^{-1} and from 9×10^{-6} °C^{-1} to 1.5×10^{-5} °C^{-1}, respectively in the axial and lateral directions and present lower values at higher deviatoric stresses. Microstructural analyses evidence tensile cracks which are interpreted to have been induced during the temperature cycles. These cracks have the potential to offset matrix thermal expansion yielding lower matrix thermal expansion coefficients at higher deviatoric stresses.

1. Introduction

The stress-dependent thermal behavior of porous rocks is particularly of interest in steam-enhanced oil recovery, geothermal reservoirs and aquifer thermal energy storage, as well as for nuclear waste repositories, the evolution of temperature in the reservoirs being more rapid than the variation of natural stress states when the life span of the systems is concerned. Pore volume contraction due to expansion of solid grains changes the storage capacity (Ashqar, 1979; Janah, 1980). Anisotropic thermal expansion within an assemblage of minerals or along the crystallographic axes of individual minerals (e.g. the crystallographic a-axes of calcite) can induce thermal cracks increasing, for instance, the risk of radioactive waste migration (Lion et al., 2005; Yavuz et al., 2010; Kozusnikova and Konecny, 2011). Furthermore, the natural stress state may alter the reservoir rock volume when the rock compressibility is modified by temperature variations (Lobree, 1968; EI-Shaarani, 1972).

Wong and Brace (1979) described the relation between the volumetric thermal expansion coefficient and the temperature-dependent bulk compressibility of rocks. Zimmerman (2000) and Guéguen and Boutéca (2004) related thermally induced rock strain to both bulk compressibility and stress state as well as temperature changes and volumetric thermal expansion coefficient. Both correlations yield implicitly that the components of rock strain due to mechanical effects and thermal expansion are temporally and spatially correlated during non-isothermal processes. Stress concentrations at grain boundaries due to applied stresses can enhance thermal cracking due to anisotropic thermal expansion (Kranz, 1983). In addition to thermal expansion, the crack-altered bulk compressibility finally contributes to bulk rock strain at a given stress state.

Ghabezloo et al. (2009) showed that the bulk thermal expansion coefficient of fluid-saturated cement paste was higher at undrained (9.6×10^{-5} °C^{-1}) than at drained conditions (6×10^{-5} °C^{-1}). It was also inferred (Ghabezloo and Sulem, 2009) that the crack-related strain, due to the pressurization of pore fluid, contributes to bulk thermal strain resulting in a higher bulk thermal expansion coefficient at undrained conditions. The length changes of three types of sandstone were measured at unstressed conditions in the temperature range from 25 °C to 1000 °C (Somerton and Selim, 1961) and also at defined stress states and drained conditions during heating from 30 °C to 175 °C (Somerton et al., 1981). In the former study, the specimens showed an

* Corresponding author.
E-mail address: peiliang@gfz-potsdam.de (L. Pei).

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irreversible increase in length after cooling. The linear thermal expansion coefficient of the tested sandstones, which were estimated from bulk strain over the respective temperature interval, did not show an obvious dependence on stress ranging from 1.5×10^{-5} °C^{-1} to 1.6×10^{-5} °C^{-1} at unstressed conditions and from 1.3×10^{-5} °C^{-1} to 2.0×10^{-5} °C^{-1} at stressed and saturated conditions. Contreras et al. (1982) and Contreras and Bermejo (1983) measured the changes in length of dry jacketed and unjacketed sandstones under hydrostatic confining stresses in the temperature range from 25 °C to 280 °C. In the latter study, hysteresis between the heating and cooling segments of the strain-temperature curves was observed. The linear thermal expansion coefficients of the sandstones, also derived from bulk strain, ranged from 8.1×10^{-6} °C^{-1} to 1.6×10^{-5} °C^{-1} at dry jacketed conditions and from 9.4×10^{-6} °C^{-1} to 2.2×10^{-5} °C^{-1} at unjacketed conditions. In the case where the dimensional changes of cylindrical rock specimens are only related to thermal expansion of the rock matrix the anisotropic thermal expansion of mineral grains (Krishnan et al., 1979) may yield different values for the thermal expansion coefficients in the axial and lateral directions of the samples. In the case where irreversible deformation occurs due to thermal cracking (Widhalm et al., 1996; Gräf et al., 2013) at a given stress state the thermal expansion coefficients calculated from bulk strain include a related mechanical component. Moreover, one-dimensional data of bulk strain would be insufficient for depicting either the overall deformation of the rock or irreversible effects during non-isothermal stages.

The present study aims at investigating the evolution of bulk strain in both the axial and lateral directions of saturated cylindrical limestone samples exposed to temperature cycles at constant hydrostatic ($\sigma_1=\sigma_3$) or deviatoric ($\sigma_1-\sigma_3$, with $\sigma_1>\sigma_3$) stress states and drained conditions; σ_1 and σ_3 are the stresses applied in the axial and lateral directions, respectively. For drained conditions, the pore pressure (p_p) is constant and independent of the applied stresses (σ_1, σ_3). We present a new method for separating the strain due to (elastic) thermal expansion or contraction of the rock matrix from the residual (irreversible) strain component in the measured bulk strain. In addition, the effect of the applied stress state on the residual strain magnitude is investigated and the matrix thermal expansion coefficients are derived. Finally, the dependence of the matrix thermal expansion coefficients on the applied stress states is investigated.

2. Sample material and experimental procedures

2.1. Sample material

Upper Jurassic Blaubeuren limestone is one of the strata in the geothermal target formations of the Molasse Basin, Germany. Its mechanical and physical properties at simulated reservoir conditions are therefore of substantial interest for site development (Homuth et al., 2014). The rock material used in the present study was sampled from a block in a quarry at Blaubeuren-Altental, Germany. This limestone is homogeneous and mainly composed of calcite showing no apparent bedding and is microstructurally dominated by oolites embedded in a fine-grained matrix (Fig. 1; see Section 2.3.4). The size of the oolites ranges from 70 μm to 100 μm while the size of calcite crystals forming them varies between 2 μm and 10 μm. Pores can be observed throughout the rock, as shown in Fig. 1. Compared with the fine-grained calcite matrix pores are more densely distributed within oolitic grains with an average pore size of 5 μm to 7 μm. The intrinsic porosity of the samples is approximately 11% as determined by mercury injection porosimetry. Cylindrical cores with a diameter of 5 cm were drilled in the same direction from the same block (40 cm × 30 cm × 30 cm) and were then surface-ground to a length of 10 cm. In a drained triaxial compression experiment (see Appendix A) this type of rock showed an elastic limit of approximately 116 MPa at a confining stress (σ_3) of 15 MPa. In the present study three rock samples labeled B2, B3, and B4 were tested.

2.2. Experimental devices

The experiments were conducted in a conventional triaxial rock deformation apparatus (MTS 815, 2004; Fig. 2; Technical Manual: 100-029-631 E; Heiland, 2003; Hassanzadegan and Zimmermann, 2014). The confining stress (σ_3) is applied by silicon oil pressurized by an external servo-controlled intensifier. The axial stress (σ_1) is generated by a servo-controlled loading piston driven by pressurized hydraulic oil and measured by a load cell in the triaxial cell. For temperature-dependent investigations three heating belts are built onto the lateral surface of the triaxial cell, which can actively heat up and passively cool down the triaxial cell, respectively. The actual temperature of the rock specimen is monitored by two thermocouples installed close to both ends of the sample.

Pore pressure (p_p) was applied by two servo-controlled syringe pumps (Quizix 6000-Series; Fig. 2). The pumps can be operated in constant pressure mode to keep the pore pressure at a defined level. When the pore volume of the specimen decreases or increases by either changes in temperature or stress this can be monitored by the pumps via the volume of pore fluid expelled from or taken up by the sample. The pumps allow for a resolution of fluid volumes as small as 1.35×10^{-5} ml and can operate at flow rates up to 200 ml/min. The maximum possible pore pressure is 68.9 MPa with a static accuracy of 0.06% (Blöcher et al., 2014).

A strain gauge-based circumferential extensometer was attached to the circumference of the rock specimens to detect their lateral deformation upon loading and during temperature cycles. The circumferential extensometer enables displacement measurements with a resolution of 1×10^{-3} mm yielding a resolution of lateral strain of 6×10^{-6} mm/mm. Absolute circumferential displacement can range between −2.5 mm and +8 mm. Axial sample deformation was measured with two strain gauge-based axial extensometers attached onto the lateral surface of the specimens. The axial extensometers enable displacement measurements with a resolution of 1×10^{-3} mm yielding a resolution of axial strain of 2×10^{-5} mm/mm. Absolute axial displacement can range between −4 mm and +7 mm. The aforementioned parameters were recorded in time intervals of 5 s.

2.3. Experimental procedures

The present study comprised three temperature cycling tests and one calibration test. For all of these experiments, axial stress (σ_1) was kept well below the elastic limit reported in Section 2.1 and the corresponding confining stress (σ_3) and pore pressure (p_p) were 15 MPa and 0.5 MPa, respectively. The stress state, once established, was kept constant during temperature cycles. The different stress states applied in the temperature cycling tests are illustrated in Fig. 3a together with the corresponding sample numbers. Prior to the tests, we performed a calibration test (see Appendix B) to assess the assembly-related offsets in thermal expansion of the rock specimens. These offsets originate from the thermal expansion of the extensometers themselves. The detailed procedure of the temperature cycling tests is described in the following.

2.3.1. Saturation

The rock specimens were first oven dried before being jacketed using a heat-shrink tubing, equipped with the extensometers, and installed in the triaxial cell. The sample assembly was then connected to the pore pressure system via tubing (Fig. 2) before being connected to a vacuum pump. The vacuum in the circuit was kept at a pressure of 6 mbar for 12 h. Subsequently, a hydrostatic confining stress ($\sigma_1=\sigma_3$) of 2 MPa was applied followed by an increase in pore pressure till 0.5 MPa. Both the upstream and downstream pore fluid pumps operated in constant pressure mode to gradually saturate the rock specimen. Deionized water was used as the pore fluid. Afterwards, the pore