Thermal over-closure of rougher joint sets – consequences for HLW disposal strategies and HTM modelling.

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1. Introduction

The writer's first experience of (ambient temperature) over-closure of rough fractures was during Ph.D. studies at Imperial College, fifty years ago, when model rock slopes (in 40,000 block tension-fracture models) excavated in 'green-field' situations would not fail at the expected slope angles. Conventional 1.1, and over-closed 4:1 and 8:1 direct shear tests (with a prior normal stress higher than in the following DST of the same rough fractures) showed successively steeper shear strength envelopes [1]. Subsequently, while at NGI, a four-cavern 20,000 blocks model, also pre UDEC, demonstrated over-closure / hysteresis since deformation was not reversed in pillars when successive caverns were excavated. [2]. The rough fracture sets were exhibiting some tensile strength and higher shear strength due to prior-to-excavation higher normal 'tectonic' $\sigma_h > \sigma_v$ boundary stresses. (see Fig. 1).

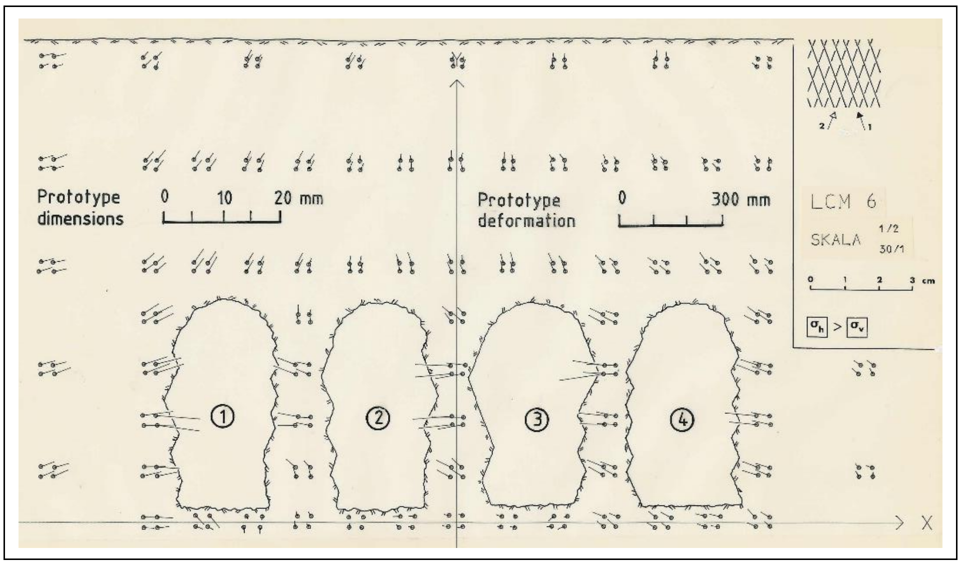

Figure 1. Caverns excavated in chronologic order 1 through 4, showing hysteresis (no reversal of deformation vectors) due to over-closure of the rough fractures, which were under higher normal stress prior to excavation.

Rough joints in igneous and metamorphic rocks can *over-close* even due to temperature increase alone, due to better fit, as conditions closer to their formation temperature are reached. Mineral-constituent thermal expansion coefficients are to blame. As a result, the *rock mass* deformation moduli, the mass thermal expansion coefficients, seismic velocities (each likely to be anisotropic), and the physical and hydraulic apertures of individual joint sets may each be affected. The initial cause is lowered normal stiffness of the roughest set of joints due to the thermal over-closure. An important side-effect: direct shear strength is increased due to the reduced physical apertures.

Well-controlled laboratory HTM tests [3], *in situ* HTM block tests [4], [5], [6] (See Figure 2), and large-scale heated rock mass tests, lasting several years at Stripa [7], Climax [8], [9] (See Figure 3), and Yucca Mountain [10] (See Figure 4), have produced evidence for this *extra* fully-coupled response. The coupled *thermal-OC* effect in HTM numerical modelling will require, as a minimum, thermal expansion coefficients that *include* rather than *exclude* relevant joint sets, if these have marked roughness and if they originated at elevated temperature. Subsequently elevated deformation moduli that attract higher stress must be expected. At least a 2:1 mismatch of rock mass deformation moduli occurred in the Climax quartz monzonite in a so-called heated ‘mine-by’ experiment in the late 1970’s, and in the large-scale heater experiment in the jointed non-lithophysal tuff at Yucca Mountain, where deformation moduli were twice as high on the heated side of a drift with apparently similar rock quality Q-values. (Figure 4).

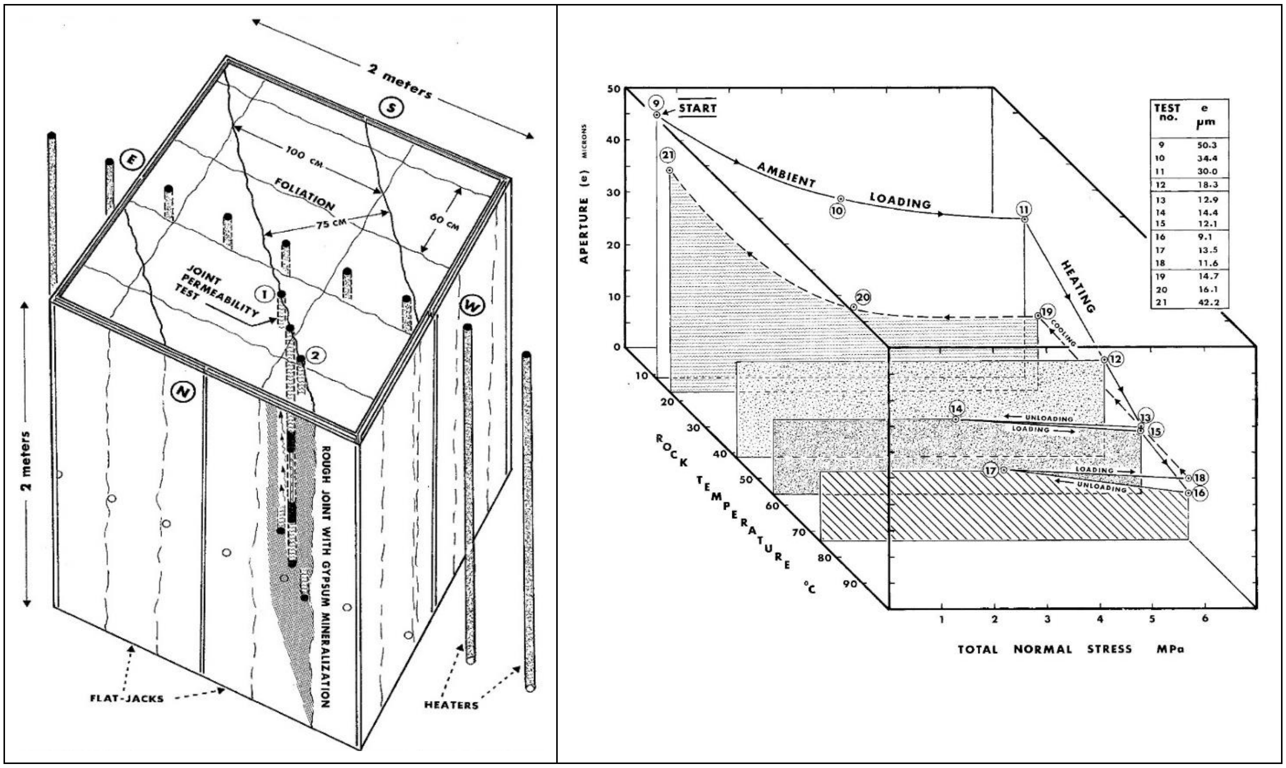

Figure 2. Schematic of TerraTek/CSM in situ 2 x 2 x 2m HTM block test showing mean joint spacings. Cross-hole permeability tests show both ambient and elevated temperature stress-aperture behavior. The tabulated apertures are the back-calculated hydraulic aperture (e). [4], [5].

2. Test evidence for thermal over-closure: summary listing

- Joint closures in laboratory HTM coupled stress flow tests (CSFT) (Makurat, NGI for AECL/URL): Increased joint closure at 60° C compared to 20°C, with further increase at 80°C. [3].

- Conducting aperture (e) decreases due to temperature increase in the Terra Tek / CSM 2 x 2 x 2m HTM in situ block test (for ONWI). Also consistent evidence of $\Delta E > \Delta e$. The reduced apertures occurred despite control of boundary flat-jack pressures during the heating. Partial recovery of apertures when cool. (Figure 2). [4], [5].

- Reduced thermal expansion coefficients at NSTF Hanford (for Rockwell-Hanford). The thermal expansion coefficients of the approx. $8m^3$ columnar basalt block which was loaded in three dimensions, showed a maximum reduction from 6.34×10^{-6} °C^{-1} over the temperature range of 18° to 60°C, to 2.59×10^{-6} °C^{-1} over the temperature range 60° to 100°C [6]. This would be caused by thermal over-closure which is easier to understand in columnar basalt.

- Conducting aperture reductions from 60 to 35μm during temperature increases through 48°, 68° to 94°C in 2 x 2 x 2m HTM in situ block test in G-Tunnel (for Sandia National Laboratory). The mean JRC_0 of the same joint set in the surrounding drift was 9 [7].

- Reduced Vp and Vs after long-term (several years) heated-then-cooled cross-hole borehole tests at Stripa (LBL/SKB). There was remarkably poor numerical model prediction of displacements, due to thermal joint over-closure and therefore changed deformation moduli [8].
- Heated mine-by (Spent Fuel Test) at Climax (Lawrence Livermore). Poor model prediction (1:2 and even up to 1:4 errors in displacement prediction) due to higher final moduli and lower thermal expansion coefficients, due to thermal-over-closure (TOC) of the joints [9], [10]. (See Figure 3).
- Increased cohesive and frictional strength of joints in welded tuff that have been heated. (Sandia National Laboratories).
- Heated and ambient sides of plate load test at Yucca Mountain, during the large-scale heater tests (DoE/Sandia). Widely different moduli were measured in the ambient and heated sides of the same drift [11]. (See Figure 4) .

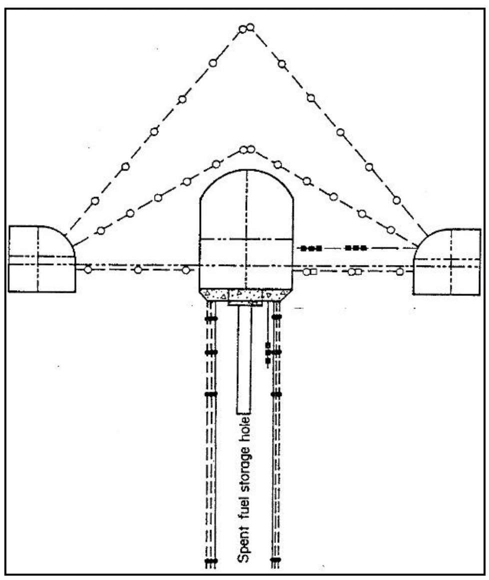

Figure 3. Heated mine-by experiment in the Climax Mine Spent Fuel Test, in quartz monzonite. [9], [10]. Strongly over-estimated deformations using ANDINA (2:1 and even 4:1) were the result of the TOC phenomena.

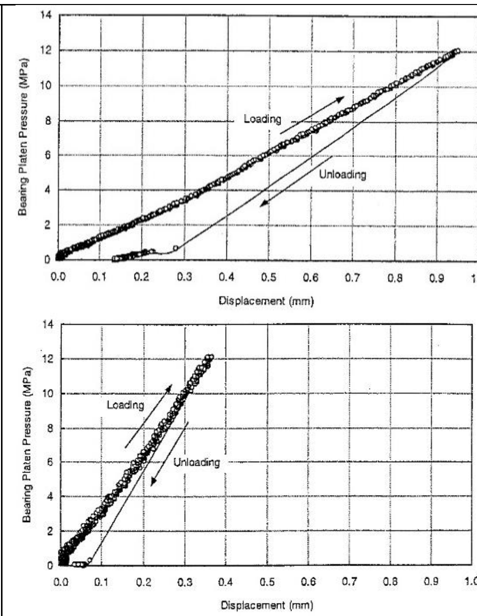

Figure 4. Yucca Mountain plate-load test performed in an adit with one side heated. E_{mass} (ambient) 11.4 GPa, E_{mass} (heated) 24.5 GPa. Each side of drift had similar Q-values.

Conclusions

1. It is suspected that the HM, HTM and HTMC modelling communities have not yet taken over-closure and thermal over-closure sufficiently seriously to attempt to allow for its potential impact in numerical modelling. Its numerous effects have not yet been included in the Barton-Bandis HM constitutive joint model, since there is need for further test results. There were glimpses of recognition during the Climax mine-by project, after the big deformation modelling errors had been confirmed following re-calibration/confirmation of instrumentation results in TerraTek in 1980/1981. This is the same period when TerraTek was performing the in situ 2 x 2 x 2m ONWI heated block test, specifically to test numerous instruments in parallel, including simple manual ones, in a heated THM environment [4], [5], [12].
2. High-level nuclear waste disposal in geologic repositories, using such schemes as envisaged by SKB and POSIVA, requires respect for jointing when siting (drilling) and actually disposing of the waste-containing copper cannisters. The phenomena of TOC (thermal over-closure) that affect

normal stiffness, deformation modulus, thermal expansion coefficients, shear strength, permeability, and seismic velocities needs additional consideration. This is quite a list for effecting the results of numerical modelling. Note the warning illustrated in Figure 5.

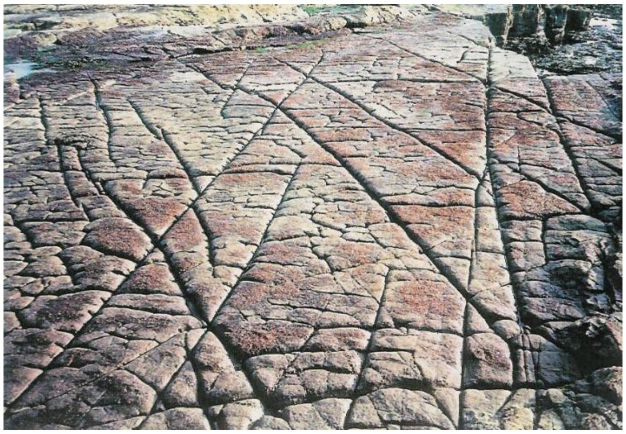

Figure 5. In an HLW disposal operation smoother and more continuous joints need wide avoidance, as they may lose shear strength and gain permeability, if the rougher joints remain thermally-over-closed during cooling.

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