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EVALUATION OF THE IMPACT OF THERMAL-HYDROLOGICAL-MECHANICAL COUPLINGS IN BENTONITE AND NEAR-FIELD ROCK BARRIERS OF A NUCLEAR WASTE REPOSITORY IN SPARSELY FRACTURED HARD ROCK

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Abstract: As part of the international DECOVALEX III project and the European BENCHPAR project, this paper evaluates the impact of thermal-hydrological-mechanical (THM) couplings on the performance of a bentonite back-filled nuclear waste repository in sparsely fractured hard rock. The significance of THM coupling on the performance of a hypothetical repository is evaluated by several independent coupled numerical analyses. Moreover, the influence of a discrete fracture intersecting a deposition hole is discussed. The analysis shows that THM couplings have the most impact on the mechanical behaviour of bentonite-rock system, which is important for repository design considerations.

1 INTRODUCTION

This paper evaluates the impact of thermal-hydrological-mechanical (THM) couplings on the performance of a bentonite-back-filled nuclear waste repository in sparsely fractured hard rock. The analysis was carried out as a part of the DECOVALEX III and BENCHPAR projects. DECVALEX III is an international co-operative research project for the development of coupled models and their validation against experiments, whereas BECHPAR is a project supported by the European Union aimed at improving the THM coupled processes content of radioactive waste repository performance assessment. In BENCHPAR/DECOVALEX III, seven research teams independently performed coupled THM analysis of a hypothetical repository, defined in Nguyen et al., (2003). The hypothetical repository consists of horizontal drifts, which are back-filled with a rock-bentonite mixture and vertical deposition holes, in which the waste canisters are embedded in bentonite (Figure 1).

This paper focuses on a repository located in sparsely fractured rock with a hydraulic conducting horizontal fracture intersecting the vertical deposition hole (Figure 1b). The analysis for the case of a homogenous intact rock (Figure 1a) is presented in Millard et al., (2003). This paper present results of coupled THM analyses conducted by four research teams: Royal Institute of Technology (KTH), Canadian Nuclear Safety Commission (CNSC), Commissariat a l'Energie Atomique de Cadarache (CEA) and Japan Nuclear Fuel Cycle Development Institute (JNC). Computer codes used and their sources are listed in Table 1.

Table 1. Research Teams, codes and their sources

Team	Code	Reference
KTH	ROCMAS	Rutqvist et al. (2001a)
CEA	Castem2000	Verpeaux et al (1989)
CNSC	FRACON	Nguyen (1996)
JNC	THAMES	Ohnishi and Kobayashi (1996)

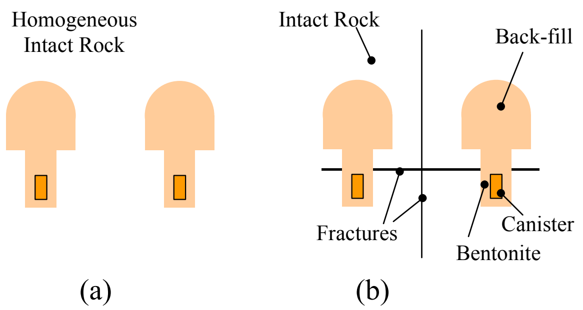


Figure 1. (a) Intact homogenous rock versus (b) sparsely fractured rock cases.

2 MODEL CONCEPTUALIZATION

The repository geometry is based on the Japanese H12 project (JNC, 2000). Because of repetitive symmetry, the simulations were conducted on a one-quarter symmetric model containing one deposition hole (Figure 2). The upper and lower boundaries are placed at vertical distances of 50 m from the drift floor according to the BMT1 definition (Nguyen et al., 2003).

Most of the material properties for bentonite and the rock were extracted or developed during DECOVALEX II for modelling of the Kamaishi Mine heater test (Rutqvist et al., 2001b). Bentonite properties were further calibrated for improved model representation of *in situ* THM responses at Kamaishi Mine (Chijimatsu et al., 2003). The rock matrix represents intact granite with a permeability varying between 1×10^{-19} and 1×10^{-17} m^2, a Young's modulus of about 60 GPa, and a thermal expansion coefficient of about $8\text{x}10^{-6}$ 1/°C.

The mechanical and hydromechanical properties of the horizontal rock fractures were estimated using the Barton-Bandis' Joint model (Barton and Bakhtar, 1983). In this context, the void aperture, b_v, is defined as the accessible volume per unit area of a fracture. The void aperture at a given effective normal stress is

$$b_v = b_{vr} + \Delta b_v \qquad (1)$$

where b_{vr} is a residual void aperture when the fracture is completely compressed from a mechanical point of view, and Δb_v is mechanically induced void aperture for an incompletely compressed fracture.

The mechanically induced void aperture can be related to the current effective normal stress, σ'_n, using Barton-Bandis' hyperbolic normal closure model according to

$$\Delta b_v = \frac{k_{n0} V_{m0}^2}{\sigma'_n + k_{n0} V_{m0}} \qquad (2)$$

where k_{n0} and V_{m0} is the normal stiffness and maximum normal closure at the zero stress intercept (Barton and Bakhtar, 1983). The parameters k_{n0} and V_{m0} were estimated using the basic parameter values $JRC_0 = 9$, $JCS_0 = 105$ MPa and $\sigma_{ci} = 123$ MPa (extracted from the Kamaishi Mine data set). Using formulas presented in Barton and Bakhtar (1983), $k_{n0} = 56$ GPa/m and $V_{m0} = 65$ μm were derived for the fourth loading cycle.

For the hypothetical case presented in this analysis we assume $b_h = 0.85\times b_v$, where b_h is the hydraulic aperture defined from the parallel plate flow relationship

$$T_f = \frac{b_h^3 \rho g}{12\mu} \qquad (3)$$

Figure 3 presents the resulting relationship between fracture transmissivity and effective normal stress. This function represents a fracture whose initial aperture is 10 μm at an initial effective stress of 17 MPa, corresponding to the initial vertical effective stress across the horizontal fracture.

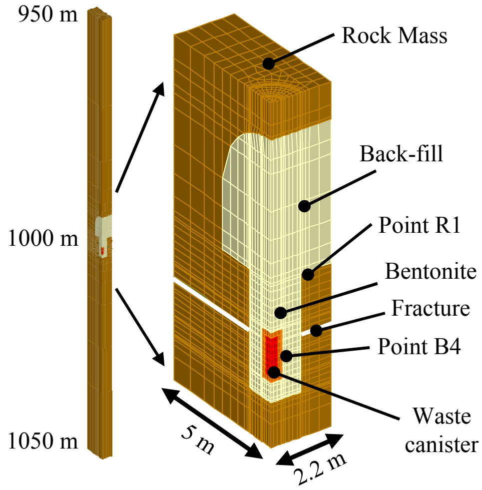


Figure 2. Quarter symmetric model of the hypothetical repository located at 1000 meters depth (KTHs model).

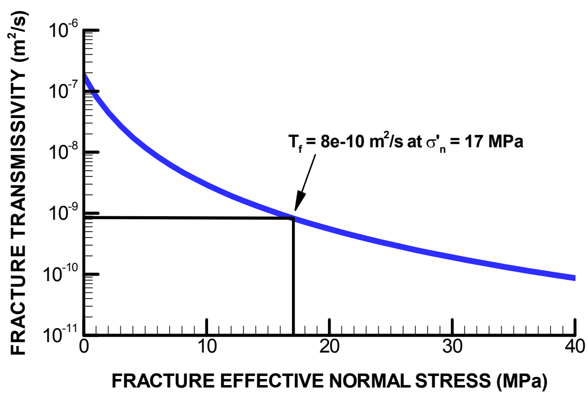


Figure 3. Fracture transmissivity versus effective fracture stress derived for k_{n0} *= 56 GPa/m and* V_{m0} *= 65 μm.*

The mechanical integrity of the rock mass is estimated using Hoek and Brown's failure criterion, which can be written as (Hoek and Brown, 1997):

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a \qquad (4)$$

where σ'_1 and σ'_3 are the maximum and minimum effective stresses at failure respectively, m_b is the values of Hoek-Brown constant m for the rock mass, s and a are constants which depends upon the characteristics of rock mass, and σ_{ci} is the uniaxial compressive strength of the intact rock pieces. In this simulation, the empirical constants have been estimated to $a = 0.5$, $m_b = 17.5$ and $s = 0.19$, which represents a very good quality rock mass of sparsely fractured granite.

3 THM MODEL RESULTS

Figure 4 summarises the general results of THM analyses by CEA, CNSC, KTH and JNC. Results of time evolution at selected points (B4 in the buffer and R1 in the rock) are shown in Figures 5 and 6.

Figure 5a shows that the maximum temperature of about 75 to 80°C is reached at the surface of the waste canister after about 30 to 40 years. The slightly lower peak temperature obtained by CNSC appears to be related to a lower initial temperature.

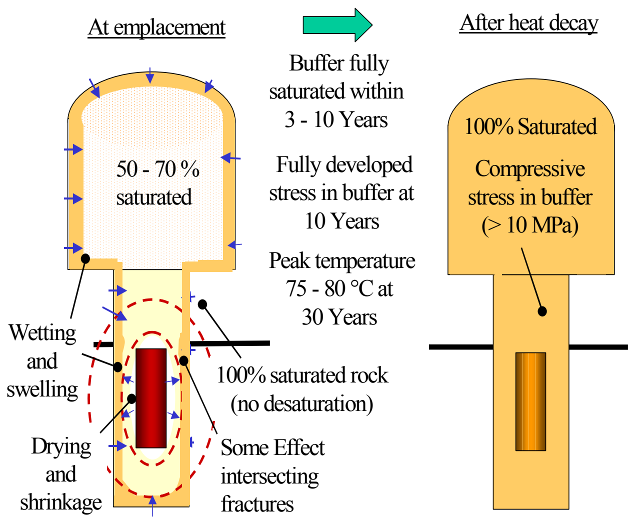
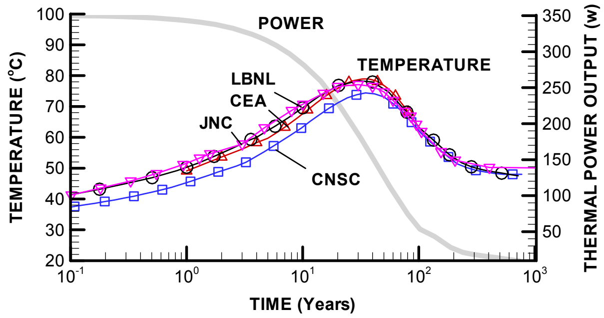
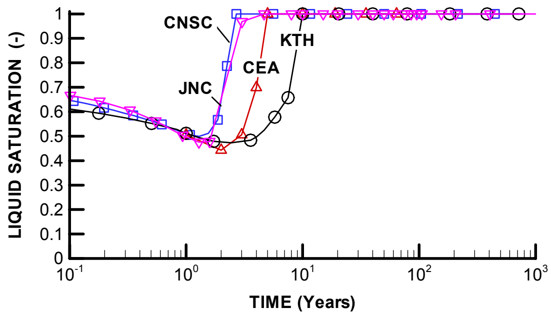


Figure 4. General results of coupled THM simulations of a hypothetical repository in sparsely fractured rock

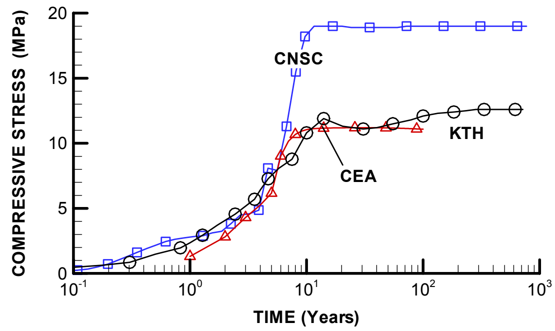
Figure 5b shows that the time to full resaturation of the buffer varies between 3 to 10 years. The different resaturation times among these models are in line with simulation results obtained for the well-defined axisymmetric problem (Chijimatsu et al., 2003) and for the case of a homogenous rock (Millard et al., 2003). This indicates that the variation of the resaturation time among these models are caused by slightly different input hydraulic properties of the buffer, such as relative permeability and water retention curves.



a) Heat power and temperature evolution



b) Evolution of liquid saturation

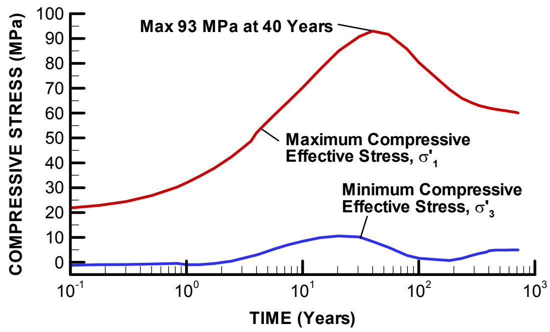


(c) Evolution of compressive stress (total stress)

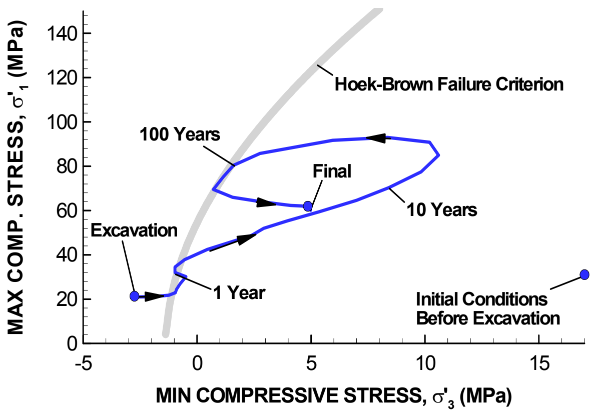
Figure 5. Simulation results by CEA, CNSC, JNC and KTH for point B4 located in the buffer at the surface of the waste canister as shown in Figure 2.

The simulated evolution of compressive stress in the buffer is very similar for CEA and KTH, whereas CNSC obtained a substantially higher compressive stress (Figure 5c). The results by CEA and KTH indicate that the impact of the fluid pressure restoration is a dominant component contributing about 90% of the total compressive stress.

Figure 6 presents the evolution of stress in the rock at point R1, which is a critical location for the evaluation of rock failure. Figure 6a shows that the maximum compressive principal effective stress is 93 MPa at about 40 years. However, Figure 6b shows that the risk for rock failure is the highest after excavation and at about 100 years, when the minimum principal effective stress is relatively small.



(a) Time evolution of σ'_1 and σ'_3

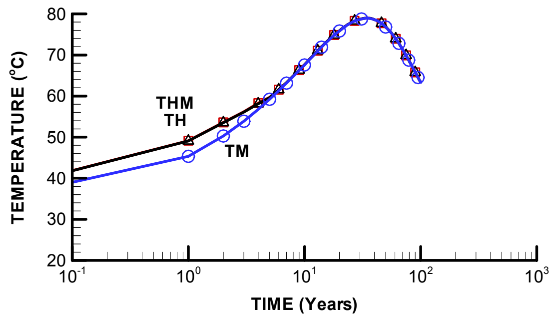


(b) Principal stress path and failure envelop

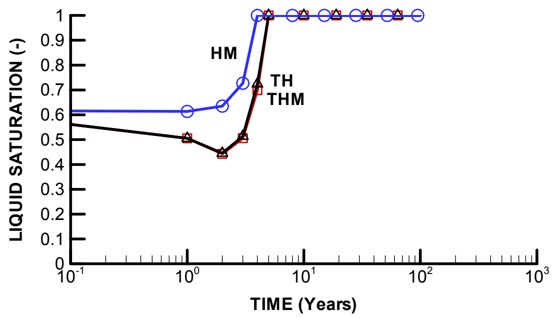
Figure 6. Simulation results by KTH showing evolution of maximum and minimum principal compressive effective stresses for point R1 located in the rock just below drift floor as shown in Figure 2.

4 IMPACT OF THM COUPLINGS

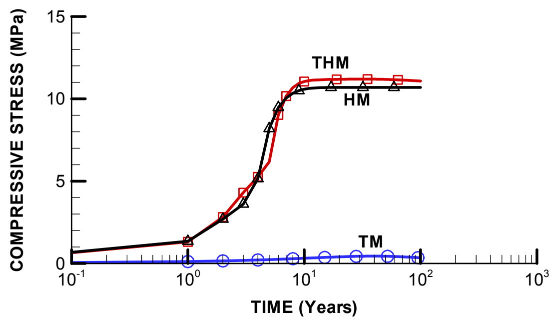
Comparisons partially coupled TH, HM and TM solutions with a fully coupled THM solution are utilised to study the impact of various couplings. Figure 7a shows that there is a small impact of TH couplings on the temperature field until the buffer is fully saturated. This slight impact of TH coupling is caused by the dependency of thermal conductive on liquid saturation. However, there is no visible impact of THM couplings on the peak temperature.



(a) Temperature evolution



(b) Evolution of liquid saturation



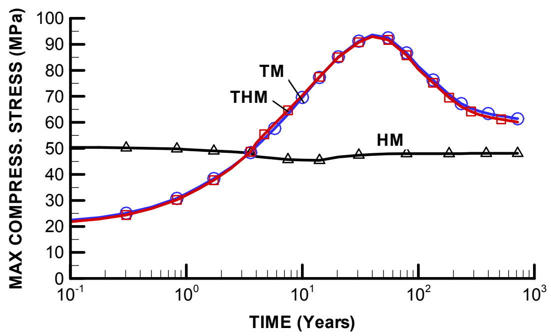
(c) Evolution of compressive stress

Figure 7. Simulation results by CEA showing the impact of HM, TH, TM and THM coupling for point B4 located in the buffer at the surface of the waste canister as shown in Figure 2.

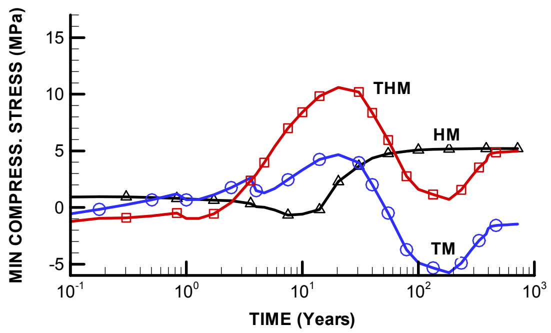
There is a slight impact of TH coupling on the resaturation of the buffer (Figure 7b). In TH and THM simulations, the resaturation of the bentonite buffer is slightly delayed because of thermally induced drying near the canister surface.

Figure 7c shows that there is a strong impact of HM coupling on the total stress in the buffer. The total stress developed in this buffer material is dominated by fluid pressure, which at 1,000 meters depths develops to 10 MPa for final hydrostatic conditions. The magnitude of TM-induced stresses is less than 1 MPa.

Figure 8a shows that the TM coupling has a dominant impact on the evolution of the maximum principal compressive stress at point R1. The evolution of the minimum principal stress is more complex, with some degree of impact from both TM and HM couplings. Nevertheless, the results in Figure 8 shows that full THM analysis must be conducted for an appropriate evaluation of the evolution of stress in the near field rock.



(a) Max compressive principal effective stress



(b) Min compressive principal effective stress

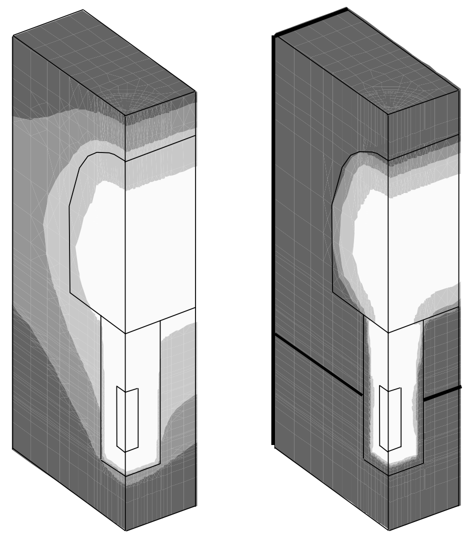
Figure 8. Simulation results by KTH showing the impact of HM, TM and THM couplings on the principal effective stress evolution for point R1 located in the rock just below drift floor as shown in Figure 2.

5 DISCUSSION ON THE IMPACT OF THE INTERSECTING FRACTURE

A comparison of simulation results for the homogenous intact rock (Figure 1a) and sparsely fractured rocks (Figure 1b) shows that the main effect of the fractures is an accelerated resaturation of the buffer leading to a much shorter resaturation time. For the case of an unfractured low permeability rock (k=1e-19 m^2), the time to full resaturation ranged from 40 to 200 years (Millard et al., 2003). By introducing hydraulic conducting fractures, the resaturation time is reduced to 3 to 10 years (Figure 7b).

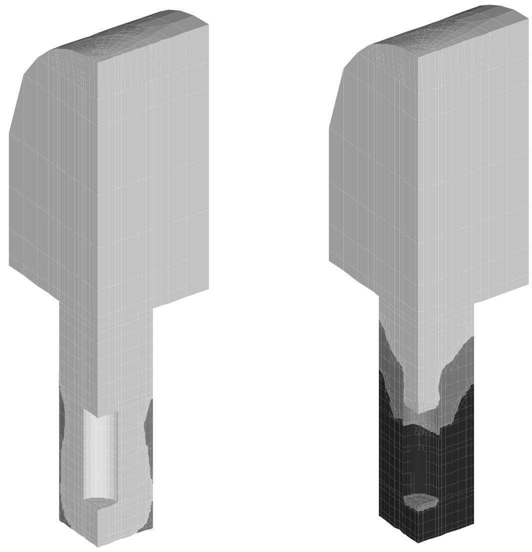
The impact of fractures is illustrated by the simulation results of KTH shown in Figure 9. For the case of a low rock matrix permeability, desaturation of the rock surrounding the repository delays the resaturation of the buffer (Figure 9a). As seen in Figure 9b, there is no such desaturation of the rock when the nearby fractures are included.

Figure 10 presents the evolution of the maximum principal compressive stress in the buffer and back-fill. Figure 10 shows that stress begins to develop near the intersecting fracture and then in the lower parts of the buffer. This result shows that an intersecting fracture impacts the stress evolution and its spatial distribution in the buffer.



(a) Intact rock (b) Fractured rock

Figure 9. Liquid saturation at 1 year from KTH simulation with ROCMAS. Darkest contour indicates fully saturated conditions whereas lightest contour indicates less than 70% saturation.



(a) 1 year (b) 10 years

Figure 10. Evolution of maximum compressive stress in the buffer and back-fill from KTH simulation with ROCMAS. Light contour indicates almost stress free conditions whereas the darkest contour indicate a fully developed compressive stress close to 10 MPa.

6 SUMMARY AND CONCLUSION

This analysis aimed to evaluate the impact of THM couplings on the performance of a repository located in sparsely fractured rock. The results of this analysis can be summarised as follows:

- **Temperature evolution (T process)** : No significant effect of H and M coupling (conduction dominates)
- **Resaturation of the buffer (H process)** : Affected by T coupling but not significantly by M coupling
- **Stress evolution in the buffer (M process)**: Strongly affected by H coupling and slightly affected by T coupling.
- **Stress evolution in rock for stability and design considerations (M process)**: Strongly affected by both T and H coupling.

It is clear that the temperature can be predicted accurately without consideration of coupling to hydraulic and mechanical processes. It is also clear that mechanical behaviour, that is, evolution of stress in the buffer-rock system, cannot be appropriately predicted without consideration of temperature effects and effects of fluid pressure. It is not clear at this point whether the hydraulic behaviour (for example resaturation of the buffer and radioactive nuclide transport) can be significantly impacted by T and M processes. For the parameter set adopted in this analysis, the resaturation time is slightly impacted by the effect of temperature whereas the mechanically induced changes in permeability does not significantly impact the resaturation process.

The general results of the impact of various THM couplings for sparsely fractured rocks conducted in this paper are in line with those of a homogenous low permeability rock (Millard et al., 2003). The main difference is that the hydraulic conducting fractures provide an additional water supply that prevents desaturation of the rock and accelerates the buffer resasuration process.

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