A Conceptual Development of Coupled Thermo-hydro-mechanical Damage (THM$_D$) Model in a Nuclear Waste Repository

Jin-Seop Kim1),*, Jun-Seo Jeon2), Min-Seop Kim2), and Geon-Young Kim1)
1) Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea
2) Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea
*kjs@kaeri.re.kr

1. Introduction

Damage evolution in a nuclear waste disposal system is one of the important issues from the perspective of a long-term safety concerns. Accumulation of damage induces changes in the mechanical, hydraulic, and thermal properties of a near-field rock [1].

The objective of this study is to propose the coupled thermo-hydro-mechanical damage (THMD) model to simulate the time-dependent long-term behaviors of disposal system.

2. Approach

2.1 General approach

Mazars damage model was applied to THM$_D$ model development with regard to the damage evolution of rock [2]. The Bacerona Basic Model (BBM) was used to simulate unsaturated and partially saturated bentonite by incorporating an extra state variable for the pore suction. The general approach for THM$_D$ model development is presented in Fig. 1. The primary code in use was Comsol MultiPhysics Ver. 5.3a.

2.2 Mass balance equations [3]

<u>Solid</u>

$$\frac{(1-n)}{\rho^s}\frac{D^s\rho^s}{Dt}-\frac{D^s n}{Dt}+(1-n)\mathrm{div}\,\mathbf{v}^s=0$$

<u>Liquid water</u>

$$\left(\frac{\alpha-n}{K_s}S_w^2+\frac{nS_w}{K_w}\right)\frac{D^s p^w}{Dt}+\frac{\alpha-n}{K_s}S_wS_g\frac{D^s p^g}{Dt}+\alpha S_w\mathrm{div}\,\mathbf{v}^s-\beta_{sw}\frac{D^sT}{Dt}+$$
$$\left(\frac{\alpha-n}{K_s}p^wS_w-\frac{\alpha-n}{K_s}p^gS_w+n\right)\frac{D^sS_w}{Dt}+\frac{1}{\rho^w}\mathrm{div}\left\{\rho^w\frac{\mathbf{k}\,k^{rw}}{\mu^w}\left[-\mathrm{grad}p^w+\rho^w(\mathbf{g}-\mathbf{a}^s-\mathbf{a}^{ws})\right]\right\}=-\frac{\dot{m}}{\rho^w}$$

<u>Gas</u>

$$\frac{\alpha-n}{K_s}S_wS_g\frac{D^s p^w}{Dt}+\frac{\alpha-n}{K_s}S_g^2\frac{D^s p^g}{Dt}-\left(n+\frac{\alpha-n}{K_s}p^cS_g\right)\frac{D^sS_w}{Dt}$$
$$-\beta_s(\alpha-n)S_g\frac{D^sT}{Dt}+\alpha S_g\mathrm{div}\,\mathbf{v}^s+\frac{nS_g}{\rho^g}\frac{D^s}{Dt}\left[\frac{1}{\theta R}\left(p^{ga}M_a+p^{gw}M_w\right)\right]$$
$$+\frac{1}{\rho^g}\mathrm{div}\left\{\rho^g\frac{\mathbf{k}\,k^{rg}}{\mu^g}\left[-\mathrm{grad}p^g+\rho^g\left(\mathbf{g}-\mathbf{a}^s-\mathbf{a}^{gs}\right)\right]\right\}=\frac{\dot{m}}{\rho^g}$$

2.3 Momentum balance equations

$$-\rho\,\mathbf{a}^s-nS_w\rho^w\left[\mathbf{a}^{ws}+\mathrm{grad}\,\mathbf{v}^w\cdot\mathbf{v}^{ws}\right]-nS_g\rho^g\left[\mathbf{a}^{gs}+\mathrm{grad}\,\mathbf{v}^g\cdot\mathbf{v}^{gs}\right]+\mathrm{div}\sigma+\rho\,\mathbf{g}=0$$

2.4 Enthalpy balance equations

$$\left(\rho C_p\right)_{\mathrm{eff}}\frac{\partial T}{\partial t}+\left(\rho_wC_p^w\,\mathbf{v}^w+\rho_gC_p^g\,\mathbf{v}^g\right)\cdot\mathrm{grad}T-\mathrm{div}(\chi_{\mathrm{eff}}\mathrm{grad}T)=-\dot{m}\Delta H_{\mathrm{vap}}$$
$$\textit{where}\quad\left(\rho C_p\right)_{\mathrm{eff}}=\rho_sC_p^s+\rho_wC_p^w+\rho_gC_p^g,\ \chi_{\mathrm{eff}}=\chi^s+\chi^w+\chi^g$$

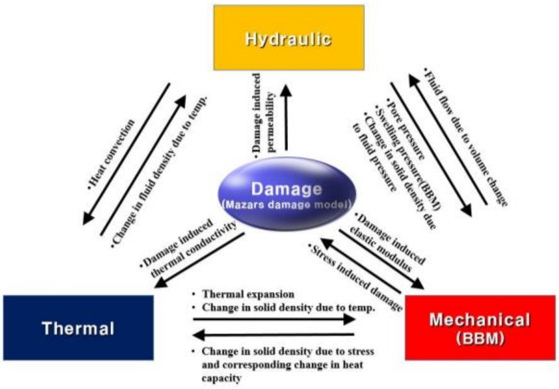

Fig. 1. A concept of coupled THM$_D$ model development.

3. Model setup

The material properties and model constants used in THM$_D$ modeling are listed in Table 1-3 below. Fig. 2 shows the model geometry and dimensions used for the developed model application.

Table 1. Material properties used in THM$_D$ model

Parameter		Bentonite	Rock	plug	Heater
Mechanical	Density of solid particle	2740	2650	2367	7850
	Dry density [kg/m^3]	1600	2650	2367	7850
	Biot's coefficient	0.8	1.0	0.8	1.0
	porosity	0.41	0.01	0.15	0.0001
	Residual porosity	-	0.009	-	-
	Young's modulus [GPa]	-	22.8	20.0	155.0
	Poisson's ratio	0.4	0.2	0.19	0.285
Hydraulic	Intrinsic permeability [m^2]	6e-20	1e-19	1e-19	-
	P_0 [MPa]	3.8	1.5	1.5	-
	m	0.25	0.595	0.595	-
	S_{lr}	0	1	1	-
	S_{ls}	1	0.01	0.01	-
	λ	3	0.595	1	-
Thermal	Thermal conductivity [W/mK]	1.299	3.3	1.2	52.5
	Specific heat capacity [J/kg/K]	1000	1210	964	440
	Thermal expansion Coefficient [1/K]	2.5e-5	7.5e-6	4.3e-6	0

Table 2. Constants in Mazars Damage Model

Rock type	ε_{d0}	A_c	B_c	A_t	B_t
Granite	3.7e-4	1	120	2	90

Table 3. Constants in Barcelon Basic Model

Bentonite	p_c [MPa]	p_0^* [MPa]	$\lambda_{(0)}$	r	β	κ_{io}	α_i
FEBEX project	0.1	14	0.15	0.75	0.05	0.05	-0.003

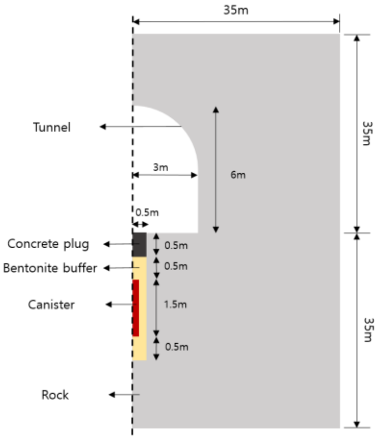

Fig. 2. Model geometry and dimensions.

4. Main Results

The variation of pore pressure, temperature and swelling pressure of bentonite with time are presented in Fig. 3-4. It is anticipated that the full saturation of bentonite is obtained after about 40 years.

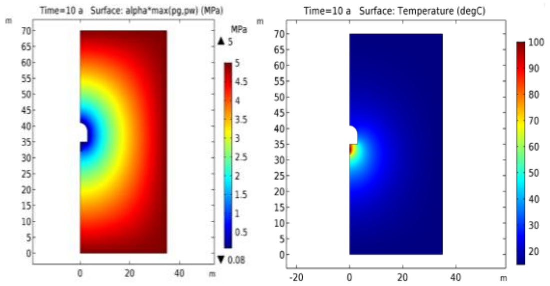

Fig. 3. Variations of pore pressure and temperature after 10 years.

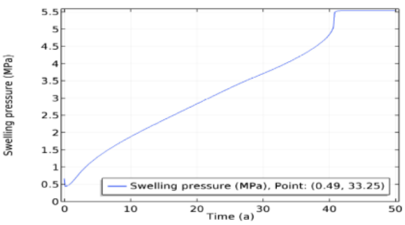

Fig. 4. Swelling pressure for 50 years.

5. Conclusion

The THM$_D$ model was conceptually developed and successfully applied to a nuclear waste repository based on the consideration of damage evolution of rock and bentonite resaturation. It is necessary to validate the developed THM$_D$ model from further study.

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