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To cite this article: Qi Zhang et al 2020 IOP Conf. Ser.: Earth Environ. Sci. 570 062023

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# Numerical investigation of coupled thermal-hydro-mechanical behavior of bentonite with joint in high-level radioactive waste disposal

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Abstract: Deep underground geological disposal is regarded as the most appropriate disposal conception for high-level radioactive waste (HLW). Bentonite is employed as buffer material placed between the surrounding rock and waste canister, and it is made into circular blocks with high densities that are stacked in the repository. However, joints between bentonite blocks are filled with crushed bentonite of low density, which has a significant influence on its mechanical and hydraulic behavior. In this paper, a coupled thermal-hydro-mechanical (THM) model is proposed to study the performance of bentonite in the repository. Extended Barcelona Basic Model is adopted to study the mechanical deformation of bentonite, while the two-phase flow model is utilized to present the migration of water and gas in bentonite. Experimental results of Gaomiaozi (GMZ) bentonite are employed to verify the effectiveness of the proposed mathematical model. Numerical simulations are conducted to obtain the evolution of saturation and temperature of bentonite using COMSOL software. The research results indicate that it takes  $7.98 \times 10^9$  s for water to flow from the outer to inner boundary. Compared with the saturated process of bentonite, significantly less time is taken to achieve heat balance. Water flows faster in the joint than in blocks, and the water flow velocity in joint increases with the permeability increment, which causes the saturation degree to decrease near point A and increase near point B.

## 1. Introduction

As one of the clean energy sources, nuclear power has a broad application prospect in many fields <sup>[1]</sup>. However, significant high-level radioactive waste (HLW) has been produced with the development of nuclear power in the last few decades. These HLWs are harmful to the environment because of their high toxicity, high radioactivity, and long half-life<sup>[2]</sup>. At present, deep underground geological disposal is an accepted conception for HLW around the world <sup>[3]</sup>. According to the preliminary concept in China, granite and bentonite are the natural barrier and engineering buffer to secure long-term safety of HLW in the repository. Bentonite plays a vital role in the safe disposal of HLW because of its low permeability, proper expansion force, and high thermal conductivity <sup>[4, 5]</sup>.

The bentonite placed between canister and surrounding rock is in a coupled thermal-hydro-mechanical (THM) condition, including thermal transfer from canister, water and gas flow from the surrounding rock and canister, and ground stress from the surrounding rock. Hence, to design and assess the engineered barriers for the safety disposal of HLW, revealing long-term

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performance of bentonite under the coupled THM condition is necessary.

Extensive studies have focused on the coupled THM behavior of buffer material in the last decades, including site and laboratory experiments together with numerical simulations <sup>[6, 7]</sup>. Long-term test of buffer material was performed in Sweden in 1985<sup>[8]</sup>. Geotechnical experiment was conducted to investigate the development of saturation in bentonite barrier in Czech Republic <sup>[9]</sup>. A full-scale engineered barriers experiment in situ test was performed at the Grimsel Test Site in Switzerland <sup>[10]</sup>. In 2011, the China-mock-up test was conducted to learn the coupled THM behavior of GMZ bentonite <sup>[11]</sup>. In addition, many efforts have been made to comprehend the properties of bentonite mixture <sup>[12-14]</sup>. In conclusion, all these experiments were able to obtain the behavior of buffer material in the repository condition.

Numerical simulation is an effective way to obtain long-term behavior of buffer material, which cannot be achieved by laboratory experiments. In 1990s, Alonso et al. introduced the classical Barcelona Basic Model (BBM) to explain the mechanical behavior of unsaturated soil<sup>[15, 16]</sup>. Since then, many coupled THM models have been established based on the BBM and employed to determine the coupled THM behavior of buffer material. Chen et al. proposed a coupled constitutive model to reproduce the coupled THM behavior of GMZ bentonite <sup>[17]</sup>. However, the joints between bentonite blocks have not been investigated and are not well understood in the previous studies.

In this paper, a coupled THM model is introduced to present the coupled THM behavior of bentonite with joint. The coupled equations are implemented and solved by COMSOL Multiphysics software.

## **2** Governing equations

To develop the governing equations for coupled THM model, the necessary assumptions made are as follows: (a) Deformation and strain of GMZ bentonite are small. (b) The GMZ bentonite is regarded as homogeneous continuum. (c) The GMZ bentonite volume is treated as a single porous media. Voids of the bentonite skeleton are partially saturated with water and gas. (d) According to the theory of mixtures, bentonite, water, and gas are treated as three independent continua.

#### 2.1 GMZ bentonite mechanical equations

To describe the mechanical behavior of bentonite buffer, a series of governing equations are adopted, including the geometry equation, equilibrium equation, and physical equation.

According to the elasticity theory, the strain-displacement relation of the bentonite can be described as follows:

$$\varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \tag{1}$$

where  $\varepsilon_{ij}$  is the total strain tensor of the bentonite; and,  $u_i$  and  $u_j$  are displacement in *i* and *j* directions, respectively.

As the heat flows from the canister to the bentonite, thermal stress is generated because of the variable temperature distribution. The equilibrium equation considering thermal stress can be deduced as follows:

$$\sigma_{ii,i} - K\alpha_T T \delta_{ii} + f_i = 0 \tag{2}$$

where  $\sigma_{ij}$  is total stress tensor of the bentonite; *K* is bulk modulus;  $\alpha_T$  is thermal expansion coefficient; *T* is temperature variable;  $\delta_{ij}$  is Kronecker delta; and  $f_i$  is body load in the *i* direction.

Bentonite remains in the unsaturated state for a long time in the repository. In 1990s, Alonso et al. proposed the BBM to explain mechanical behavior of unsaturated soil, in which three independent variables, including suction, net mean stress, and deviatoric stress, were utilized to explain the stress-

strain relation of soil. In 2011, a modification of the BBM (BBMx) was proposed to simplify its implementation in simulations using the finite element method<sup>[18]</sup>. Therefore, the BBMx is adopted for the stress–strain relationship of bentonite in this paper.

## 2.2 Two-phase (water and gas) fluid flow equations

In the repository, gas and water from microbial decomposition (near canister) and ground water inflow (surrounding rock) simultaneously transfer in the bentonite. With the increase of bentonite saturation caused by water inflow, the flow of water and gas are affected because of the corresponding change of relative permeability. Hence, a two-phase fluid flow model is introduced as follows:

2.2.1 Water transport equations. The water continuity equation for expressing water flow in the bentonite can be induced is as follows:

$$\frac{\partial m_w}{\partial t} + \nabla \cdot (\rho_w q_w) = Q_w \tag{3}$$

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where  $m_w = \rho_w \varphi s_w$  is the water mass per volume of bentonite;  $\varphi$  is the porosity of bentonite;  $s_w$  is the saturation degree;  $\rho_w$  and  $q_w$  are the water density and seepage velocity, respectively;  $Q_w$  is the water source; and t is the time variable.

According to the Darcy's law, water seepage velocity in bentonite can be defined as follows:

$$q_{w} = -\frac{k \cdot k_{rw}}{\mu_{w}} \nabla p_{w} \tag{4}$$

where k is the intrinsic permeability of the saturated bentonite;  $k_{rw}$  is the water relative permeability;  $\mu_w$  is the dynamic viscosity of water. In fact, dynamic viscosity of water decreases dramatically with the increase of temperature, as shown in Figure 1.





The saturation degree of bentonite determines its water relative permeability. According to Luckner et al.<sup>[19]</sup>, the relationship between bentonite saturation degree and water relative permeability can be described by equation (5):

$$k_{rw} = s_w^{\ l} [1 - (1 - s_w^{\ 1/m})^m]^2$$
(5)

where l is a parameter of equation (5).

The saturation degree of bentonite varies with the water content of bentonite. According to the Van Genuchten model <sup>[20]</sup>, saturation degree can be calculated using pore water pressure and pore gas pressure:

$$s_{w} = \left[1 + \left(\frac{p_{g} - p_{w}}{p_{r}}\right)^{n}\right]^{-m}$$
(6)

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where  $p_g$  and  $p_w$  are the pore gas pressure and pore water pressure, respectively.  $p_r$ , n and m are parameters of the VG model.

In the two-phase fluid flow model,  $s_w$  and  $p_g$  are chosen as independent variables. Thus, equation (6) can be written as follows:

$$p_{w} = p_{g} - p_{r} (s_{w}^{-\frac{1}{m}} - 1)^{\frac{1}{n}}$$
(7)

The gradient of  $p_w$  is induced in equation (8),

$$\nabla p_w = \nabla p_g - p_r \cdot dpw \_ sw \cdot \nabla s_w \tag{8}$$

where  $dpw_sw = \frac{1}{n} \cdot (s_w^{-\frac{1}{m}} - 1)^{\frac{1}{n-1}} \cdot (-\frac{1}{m}) \cdot s_w^{-\frac{1}{m-1}}$ .

Substituting equations (4) and (8) into equation (3), water continuity equation is induced as

$$\varphi \frac{\partial s_w}{\partial t} - \nabla \cdot \left( \frac{k \cdot k_{rw}}{\mu_w} \cdot \left( \nabla p_g - p_r \cdot dpw \_ sw \cdot \nabla s_w \right) \right) = Q_w \tag{9}$$

#### 2.2.2 Gas transport equations.

Gas continuity equation for expressing gas seepage in bentonite can be written as follows:

$$\frac{\partial m_g}{\partial t} + \nabla \cdot (\rho_g q_g) = Q_g \tag{10}$$

where  $m_g = \rho_g \varphi(1 - s_w)$  is the gas mass per volume of bentonite;  $\rho_g$  and  $q_g$  are gas density and gas seepage velocity respectively; and  $Q_g$  is the gas source.

According to the Darcy's law, seepage velocity of gas in bentonite is calculated as follows:

$$q_g = -\frac{k \cdot k_{rg}}{\mu_g} \nabla p_g \tag{11}$$

where  $k_{rg}$  is the gas relative permeability;  $\mu_g$  is the dynamic viscosity of water. Dynamic viscosity of gas as a function of temperature has been demonstrated in Figure 2.



## Figure 2. Viscosity of air versus temperature

The gas in bentonite is assumed as an ideal gas. Thus, gas density is determined by the gas pressure and temperature:

$$\rho_g = \frac{p_g M_g}{RT} \tag{12}$$

where  $M_{g}$  is relative molecular mass of gas; R is constant value of the ideal gas.

According to the Van Genuchten model, the relationship between gas relative permeability and bentonite saturation degree can be expressed as follows:

$$k_{rg} = (1 - s_w)^l (1 - s_w^{-1/m})^{2m}$$
(13)

Substituting equations (11) and (12) into equation (10), the gas continuity equation can be written as equation (14):

$$(1-s_w) \cdot \varphi \frac{\partial p_g}{\partial t} - p_g \cdot \varphi \frac{\partial s_w}{\partial t} - \nabla \cdot (p_g \cdot \frac{k \cdot k_{rg}}{\mu_g} \nabla p_g) = Q_g$$
(14)

## 2.3 Energy balance equation

The canister continues to generate large amounts of heat because of radioactive waste decay. The heat transfer in bentonite satisfies the Fourier's law. Thus, the energy balance equation can be written as follows:

$$c_f \rho_f \frac{\partial T}{\partial t} + c_f \rho_f v \cdot \nabla T - \nabla (\lambda \cdot \nabla T) = q_t$$
(15)

where  $c_f = s_w \cdot c_w + (1 - s_w) \cdot c_g$  is the heat capacity of the fluid; and,  $c_w$  and  $c_g$  are heat capacity of water and gas, respectively.  $\rho_f = s_w \cdot \rho_w + (1 - s_w) \cdot \rho_g$  is the density of the fluid;  $\nu$  the is heat advection velocity;  $q_t$  is the heat source per unit volume; and  $\lambda$  is the thermal conductivity of the media, where media means bentonite with water and gas. According to the laboratory experiments, thermal conductivity of bentonite can be expressed as

$$\lambda = 1.6 \cdot s_w + 0.02 \tag{16}$$

## **3** Numerical settings

#### 3.1 Model geometry

In this part, the model geometry, parameters, and boundary settings for the coupled THM simulation of bentonite with joint are introduced. The calculation model is a 2D plane cross-section through the repository. It is a plane circle of diameter of 1.8 m and a borehole of diameter of 0.6 m in the center. Figure 3 presents different forms of bentonite blocks splicing, in which gaps between the bentonite blocks are filled with low density bentonite. Note that the thickness of the joint is 5 mm in all forms of bentonite block splicing. As for the boundary settings, the inner boundary suffers from gas and heat inflow from microbial decomposition and canister, while the outer boundary suffers from water inflow and ground stress from the surrounding rock. In this paper, the gas flow rate and temperature at the inner boundary are  $10^{-12}$  m/s and 363.15 K, respectively. Further, the water flow rate at the outer boundary is  $10^{-11}$  m/s. The initial saturation degree and temperature of bentonite blocks are 0.2 and 293.15 K, respectively.



Figure 3. Different forms of bentonite blocks splicing: (a) intact; (b) two joints; (c) four joints; (d) six joints; (e) eight joints.

#### 3.2 Parameters

The bentonite buffer is composed of high density compact bentonite block and low density bentonite joints. Different bentonite densities have a significant impact on its porosity, permeability, and thermal conductivity. Table 1 tabulates difference of parameters between the bentonite block and joint. **Table 1.** Difference of parameters between the bentonite block and joint

Parameters	Bentonite block	Joint	
Density	1700 kg/m <sup>3</sup>	1400 kg/m <sup>3</sup>	
Void ratio	0.565	0.9	
Porosity	0.3609	0.4737	
Permeability	$1.1 \times 10^{-20} \text{ m}^2$	$1.03 \times 10^{-19} \mathrm{m}^2$	

Since the coupled THM behavior of bentonite is discussed in this paper, parameters related to the bentonite mechanical properties as well as gas and water flow properties are given in Table 2. Table 2. Parameters used in numerical simulations

Parameters	Values
Soil shear modulus	10 MPa <sup>[15]</sup>
Swelling index	$0.027^{[17]}$
Swelling index for changes in suction	$0.008^{[18]}$
Compression index at saturation	$0.18^{[17]}$
Angle of internal friction	$0.167 \text{ rad}^{[21]}$
Weight Parameter	$0.65^{[17]}$
Soil stiffness parameter	$0.184 \text{ MPa}^{[15]}$
Plastic potential smoothing parameter	$10000^{[18]}$
Tension to suction ratio	$0.6^{[18]}$
Initial yield value for suction	$80 \text{ MPa}^{[17]}$

Reference pressure	$0.45 \text{ MPa}^{[17]}$
Initial consolidation pressure	$0.6 \text{ MPa}^{[17]}$
Water density	$1000 \text{ kg/m}^3$
Thermal conductivity of water	0.6 W/(mK) <sup>[22]</sup>
Water heat capacity at constant pressure	4180 J/(kg.K) <sup>[23]</sup>
Air density	$1.205 \text{ kg/m}^{3[17]}$
Thermal conductivity of air	0.26 W/(m.K) <sup>[22]</sup>
Air heat capacity at constant pressure	1000 J/(kg.K) <sup>[23]</sup>

## *3.3 Implementation of the numerical model*

The governing equations to simulate the coupled THM behavior of bentonite with joints, calculation model, parameters, and boundary settings have been established above. However, obtaining an analytic solution because of the complexity coupled relationship among mechanical deformation, fluid flow, and heat transfer is difficult. The finite element method (FEM) is adopted to solve the coupled governing equations via COMSOL Multiphysics software.

The governing equations of bentonite deformation, water and gas seepage, and thermal conductivity are induced into the final version. A pre-arranged COMSOL Solid Mechanics Module with extended Barcelona Basic model is employed to solve mechanical deformation. The two-phase fluid flows are implemented with equations (9) and (14) using COMSOL General Form PDE interface. COMSOL Heat Transfer in Porous Media Module is employed to solve the heat transfer component with equation (15).

## 4 Verification of the results

Prior to employing the proposed model to simulate the coupled THM behavior of bentonite with joints, validating the effectiveness of the model is important. The proposed model is verified by comparing the simulation results with the results of the laboratory experiments. In a repository, permeability and thermal conductivity of bentonite play an essential role in water and gas flow as well as heat advection. Figure 4 demonstrates water relative permeability of GMZ bentonite versus saturation degree obtained by numerical simulations and laboratory experiments. As observed, the increase of water relative permeability with the increase of saturation degree is depicted in Figure 5. Thermal conductivity of GMZ bentonite linearly increases with the increase of the saturation degree. We can conclude that the numerical results well agree with the laboratory results.



Figure 4. Comparison of numerical simulation and experimental data for water relative permeability



Figure 5. Comparison of numerical simulation and experimental data for thermal conductivity

## **5** Discussions

#### 5.1 Response analysis of bentonite

In this section, numerical simulations are performed to study the coupled THM behavior of the intact bentonite. The evolution of bentonite saturation and temperature are discussed as follows.

## 5.1.1 Evolution of bentonite saturation.

Figure 6 presents the evolution of bentonite saturation degree versus time. The initial bentonite saturation is set at 0.2. As time goes on, water flows into bentonite, which results in the increase of bentonite saturation degree, correspondingly. At the time  $1.04 \times 10^9$  s, saturation degree of bentonite near the outer boundary increases to 0.55, while that of the other areas is kept at 0.2. With time increment, saturation degree of bentonite gradually increases. When time is  $4.05 \times 10^9$  s, more than half of the bentonite increases its saturation degree because of the water inflow from the outer boundary. When it comes to  $7.98 \times 10^9$  s, water from the outer boundary reaches the inner boundary, which increases the saturation degree of the entire bentonite.





Figure 6. Evolution of saturation degree with time, (a) 96 s; (b)  $1.04 \times 10^9$  s; (c)  $4.05 \times 10^9$  s; (d) 7.98  $\times 10^9$  s

#### 5.1.2 Evolution of bentonite temperature.

Large amount of heat is continually generated because of the decay of nuclear waste. The evolution of bentonite temperature with time is presented in Figure 7. The inner boundary close to the canister is set at 363 K. When time is 61892 s, the temperature of bentonite near the inner boundary correspondingly increases by heat convection. With time increment, heat gradually transfers from inner boundary to outer boundary. At  $2.35 \times 10^6$  s, temperature of the entire bentonite increases to 363.15 K. Note that the saturation degree of most area is still at initial value at the time  $2.35 \times 10^6$  s. Thus, thermal conductivity is almost at 0.34 during the heating process according to equation (16). Compared with the saturated process of bentonite, it takes significantly less time to achieve heat balance.





Figure 7. Evolution of temperature with time, (a) 96 s; (b) 61892 s; (c)  $2.89 \times 10^5$  s; (d)  $2.35 \times 10^6$  s

## 5.2 The influence of various forms of bentonite blocks splicing

This section discusses the impact of various forms of bentonite block splicing on the behavior in the coupled THM condition. Four kinds of bentonite block splicing forms are adopted here, including two, four, six, and eight joints. Figure 8 depicts the distribution of saturation degree under these four bentonite block splicing forms. The joint with higher permeability promotes water flowing along it under all four conditions. However, water flows only a little bit faster in joints compared to the blocks.





Figure 8. Distribution of saturation degree under various forms of bentonite block splicing, (a) two joints; (b) four joints; (c) six joints; (d) eight joints

## 5.3 The influence of the joint permeability

In this section, the influence of joint permeability on bentonite behavior is simulated and discussed. Three different permeability are employed in numerical simulations, which are  $1 \times 10^{-19}$  m<sup>2</sup>,  $5.5 \times 10^{-19}$  m<sup>2</sup>, and  $1 \times 10^{-18}$  m<sup>2</sup>, respectively. In addition, bentonite with four joints is employed in this section. Distribution of saturation degree under the three mentioned permeability is demonstrated in Figure 9. Water flows faster in the joints compared to the blocks, and water flow velocity in joints increases with the increase of permeability. Figure 10 is the evolution of saturation degree along the joint (Line AB) with various joint permeability. With increasing joint permeability, the saturation degree near point A decreases while that near point B increases.



(a)



Figure 9. Distribution of saturation degree with various joint permeability at time  $4.05 \times 10^9$  s, (a)  $1 \times 10^{-19}$  m<sup>2</sup>; (b)  $5.5 \times 10^{-19}$  m<sup>2</sup>; (c)  $1 \times 10^{-18}$  m<sup>2</sup>



Figure 10. Evolution of saturation degree along the joint (line AB) with various joint permeability at time  $4.05 \times 10^9$  s

#### **6** Conclusions

The safely disposal of HLW is a very basic issue for securing sustainable development of nuclear power. Deep underground geological disposal is considered as the most promising method for HLW disposal. Bentonite plays a vital role in the repository because of its low permeability, proper expansion force, and high thermal conductivity. In this paper, a coupled THM model was introduced to investigate the coupled THM behavior of bentonite with joints. Then, the proposed model was verified by comparing the results with those collected through laboratory experiments. Finally, the impact of joints on water seepage and heat transfer is simulated and discussed. The following conclusions were obtained.

(1) The initial bentonite saturation is set at 0.2. As time goes on, water flows into bentonite, which correspondingly results in the increase of bentonite saturation degree. With time increment, the saturation degree of bentonite gradually increases. When it comes to  $7.98 \times 10^9$  s, water from the outer boundary reaches the inner boundary, increasing the saturation degree of the entire bentonite. Compared to the saturation process of bentonite, it takes significantly less time to achieve heat balance.

(2) We verified that water flows faster in the joints compared to the blocks, and water flow velocity

in joints increases with the increase of permeability. This consequently results in the saturation degree near point A decreasing while that near point B increasing.

### References

- [1] Forsberg CW, 2009 Sustainability by combining nuclear, fossil, and renewable energy sources *Progress in Nuclear energy* **51** 192-200
- [2] Ewing RC, Weber WJ and Clinard Jr FW 1995 Radiation effects in nuclear waste forms for high-level radioactive waste *Progress in nuclear energy* **29** 63-127
- [3] Wang J 2010 High-level radioactive waste disposal in China: update 2010 Journal of Rock Mechanics and Geotechnical Engineering 2 1-11
- [4] Villar MV and Lloret A 2008 Influence of dry density and water content on the swelling of a compacted bentonite *Applied Clay Science* **39** 38-49
- [5] Villar MV, Martin PL and Barcala JM 2005 Modification of physical, mechanical and hydraulic properties of bentonite by thermo-hydraulic gradients *Engineering Geology* **81** 284-297
- [6] Zhang Q, Ma D, Wu Y and Meng F 2018 Coupled thermal-gas-mechanical (TGM) model of tight sandstone gas wells *Journal of Geophysics and Engineering* **15**, 1743-1752
- [7] Zhang Q, Ma D, Liu J, Wang J, Li X and Zhou Z 2019 Numerical simulations of fracture propagation in jointed shale reservoirs under CO2 fracturing *Geofluids*
- [8] Pusch R, Borgesson L and Ramqvist G 1985 Final Report of the BufferMass Test-Volume II: Test Results Swedish Nuclear Fuel and Waste Management Company (SKB) Stockholm Sweden.
- [9] Pacovsky' J, Svoboda J and Zapletal L 2007 Saturation development in the bentonite barrier of the Mock-Up-CZ geotechnical experiment *Phys. Chem. Earth, Parts A/B/C* **32** 767–779
- [10] Villar MV and Lloret A 2007 Dismantling of the first section of the FEBEX in situ test: THM laboratory tests on the bentonite blocks retrieved *Phys. Chem. Earth, Parts A/B/C* 32 716– 729
- [11] Chen L, Liu YM, Wang J, Cao SF, Xie JL, Ma LK, Zhao XG and Liu J 2014 Investigation of the thermal-hydro-mechanical (THM) behavior of GMZ bentonite in the China-Mock-up test *Engineering geology* 172 57-68
- [12] Xu L, Ye WM, Chen B, Chen YG, and Cui YJ 2016 Experimental investigations on thermo-hydro-mechanical properties of compacted GMZ01 bentonite-sand mixture using as buffer materials *Engineering Geology* 213 46-54
- [13] Wang Q, Cui YJ, Tang AM, Barnichon JD, Saba S, and Ye WM 2013 Hydraulic conductivity and microstructure changes of compacted bentonite/sand mixture during hydration *Engineering Geology* 164 67-76
- [14] Liu X, Cai G, Liu L, Liu S, and Puppala, AJ 2019 Thermo-hydro-mechanical properties of bentonite-sand-graphite-polypropylene fiber mixtures as buffer materials for a high-level radioactive waste repository *International Journal of Heat and Mass Transfer* 141 981-994
- [15] Alonso EE, Gens A and Josa A 1990 A constitutive model for partially saturated soils *Géotechnique* **40** 405-430
- [16] Alonso EE, Vaunat J and Gens A 1999 Modelling the mechanical behaviour of expansive clays Engineering geology 54 173-183
- [17] Chen L, Wang J, Liu Y, Collin F and Xie J 2012 Numerical thermo-hydro-mechanical modeling of compacted bentonite in China-mock-up test for deep geological disposal *Journal of Rock Mechanics and geotechnical engineering* 4 183-192
- [18] Pedroso DM and Farias MM 2011 Extended Barcelona basic model for unsaturated soils under cyclic loadings Computers and Geotechnics 38 731-740
- [19] Luckner L, Van Genuchten MT and Nielsen DR 1989 A consistent set of parametric models for the two-phase flow of immiscible fluids in the subsurface Water Resources Research 25 2187-2193

- [20] Van Genuchten MT 1980 A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1 *Soil science society of America journal* **44** 892-898
- [21] Chen H, Lv HB, Chen ZH and Qin B 2018 Strength and volume change of buffer material under high temperature and pressure *Chinese Journal of Rock Mechanics and Engineering* 37 1962-1979 (in Chinese)
- [22] Wang X, Shao H, Wang W, Hesser J and Kolditz O 2015 Numerical modeling of heating and hydration experiments on bentonite pellets *Engineering geology* **198** 94-106
- [23] Zhao J, Chen L, Collin F, Liu Y and Wang J 2016 Numerical modeling of coupled thermal-hydro-mechanical behavior of GMZ bentonite in the China-Mock-up test. *Engineering geology* 214 116-126