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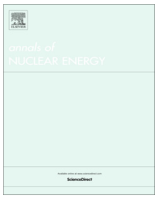

Coupled thermal-hydro analysis of unsaturated buffer and backfill in a high-level waste repository

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ABSTRACT

The buffer and backfill are the major components of an engineered barrier system (EBS) for a high level waste (HLW) repository. Reliable EBS performance assessment requires the delicate numerical modeling of the buffer and backfill. This study carried out the sensitivity analysis of thermal-hydro (TH) model parameters, and based on its results, the coupled TH analysis of an unsaturated buffer and backfill in an HLW repository. The temperature distribution was sensitive to a change in the degree of saturation and thus the thermal conductivity, and the degree of saturation distribution was sensitive to a variation in temperature and thus water viscosity. The decay heat of HLW from a canister dissipated out through the buffer and backfill into the surrounding rock. The temperature was higher closer to the canister and was lower farther from the canister. The temperature in the backfill was overall lower than that in the buffer, but both temperatures were approached slowly over a long time. The peak temperature was located at the center of the interface line between the canister and buffer, and was 107 °C at the elapsed time of 0.47 year. Re-saturation occurred in the order of the backfill and then a buffer as groundwater was intruded from the surrounding rock. The wetting of the backfill was initiated from the wall of the tunnel and the upper wall of deposition hole, and it then proceeded toward the inside. The buffer was wetted from the wall of the deposition toward the canister. The latest re-saturation location was a bit above from the center axis of the canister, at which the re-saturation period of time was estimated to be about 10 years.

1. Introduction

The Korean Reference Disposal System (KRS) for the disposal of high-level wastes will be constructed in bedrock several hundred meters below the ground surface, and will be of a room-and-pillar design, which includes a network of access tunnels and disposal rooms with vertical shafts extending from the surface to the access tunnels (Choi et al., 2008). The high-level waste (HLW) encapsulated in a canister is deposited in an array of large-diameter boreholes (Φ 2.24 m) drilled into the floors of the disposal rooms, and after emplacement of the canister, the gap between the canister and wall of the borehole is filled with a compacted bentonite buffer material. When all the boreholes in a disposal room are filled, the room is backfilled with a compacted bentonite (30%) -sand (70%) mixture (Fig. 1).

The buffer and backfill are the key barrier components of an engineered barrier system (EBS) for an HLW repository, and their major functions are to restrict the intrusion of groundwater into the repository, to release the decay heat from the waste toward the outside, to protect the waste and canister from external impact, and ultimately, to minimize the release of radionuclides into the surrounding host rock. However, the coupled thermal-hydro-mechanical (THM) process in the buffer and backfill, which occurs due to the heat generation from waste, the intrusion of groundwater from the surrounding rock, and the swelling stress of the buffer and backfill material such as bentonite, is complicated and non-linear, and also significantly influences the performance of the buffer and backfill. Therefore, it has been a critical issue in the performance assessment of the EBS for an HLW repository.

To analyze the coupled THM behavior of the buffer and backfill, researches have been carried out over the past decades: the development of computer simulation programs (Noorishad et al., 1984; Thomas et al., 1996; Olivella et al., 1996; Cleall et al., 2006; Rutqvist et al., 2008), validation of the developed programs using laboratory and in situ tests (Chandler et al., 1998; Chijimatsu et al., 1999; ENRESA, 2000; Lee et al., 2008; SKB, 2009; 2012; Li et al., 2010; NAGRA, 2011; SKB, 2012), and application of the

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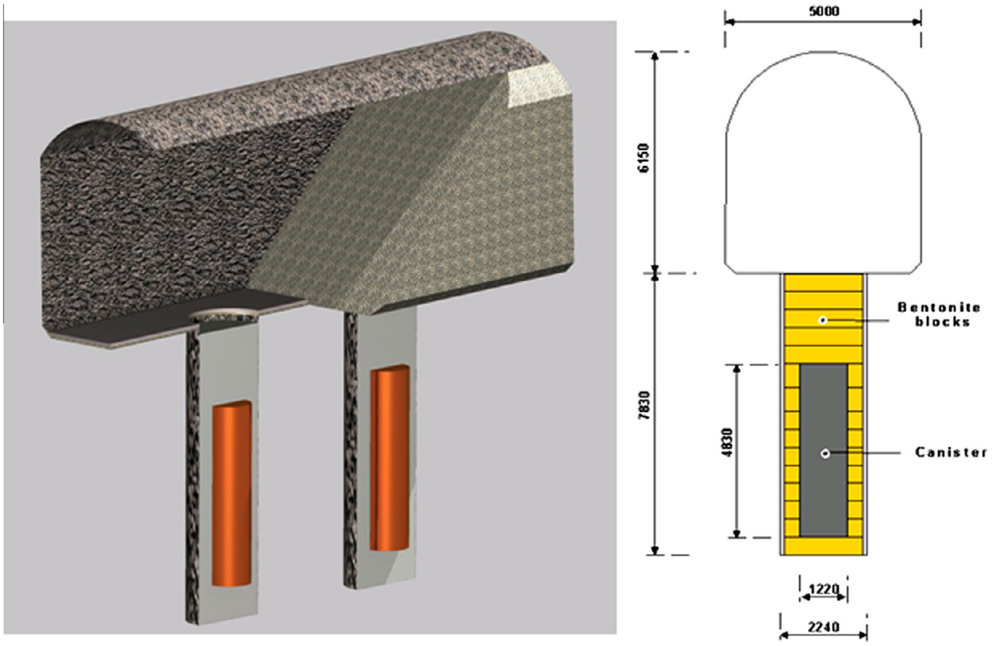

Fig. 1. Schematic picture of the engineered barrier system of the Korean Reference Disposal System (KRS).

validated simulation programs to the THM analysis of the buffer and backfill (Onofrei and Gray, 1996; Collin et al., 2002; Olivella and Gens, 2005; Chen et al., 2009; Cho et al., 2010; Kwon et al., 2012; Lee et al., 2013). The THM analyses of the buffer and backfill have been conducted on the basis of T/H/M/TM/TH/THM-models. In these models, the temperature distribution depends largely on the thermal conductivity, which is a key parameter controlling the dissipation of decay heat from the waste into the surrounding rock, and the degree of saturation distribution in the buffer and backfill depends on the density and viscosity of the groundwater. However, these model parameters were assumed to be constant in a number of THM analyses (Simmons and Baumgartner, 1994; Vieno and Nordman, 1999; JNC, 2000; ANDRA, 2001; Olivella and Gens, 2005; Ikonen, 2008; Chen et al., 2009; Cho et al., 2010; Kwon et al., 2012; Lee et al., 2013). Under real repository conditions, the thermal conductivity in the buffer and backfill is not constant. This is because, after closure of the repository, groundwater is intruded from the surrounding rock and the re-saturation of the buffer and backfill occurs. The thermal conductivity of the buffer and backfill is a function of the degree of saturation (Ikonen, 2003; Borgesson and Falth, 2006; Kim et al., 2013). An increase in the degree of saturation in the buffer and backfill by the groundwater intrusion leads to an increase in the thermal conductivity, which results in a decrease of temperature in the buffer and backfill. Meanwhile, the density and viscosity of water is a function of temperature (Dean, 1992). In the repository, the decay heat from the waste may affect the density and viscosity of water and thus the degree of saturation in the buffer and backfill. Therefore, the change of thermal conductivity due to the re-saturation of the buffer and backfill as well as the change of water density and viscosity due to the decay heat (i.e., temperature change) should be considered in the THM analysis of the buffer and backfill for the reliable performance assessment of an HLW repository.

In this connection, a sensitivity analysis was conducted in this study to examine the effect of the degree of saturation on the thermal conductivity and thus the temperature distribution, and to examine the effect of temperature on the density and viscosity of water and thus the degree of saturation. Based on the results of the sensitivity analysis, a coupled TH analysis is also carried out to investigate the temperature distribution and degree of saturation in the buffer and backfill of the KRS repository.

2. Numerical modeling and material properties

2.1. Code and model

In the present study, the thermal-hydro analysis of an unsaturated buffer and backfill was carried out using the Heat Transfer Module and Subsurface Flow Module of COMSOL Multiphysics ver. 4.2, which is a finite element computer code (COMSOL, 2011). In the Heat Transfer Module, the following governing equation, which is applicable to a conductive heat transfer in porous media, is used:

$$\rho Cp\frac{\partial T}{\partial t} + \nabla \cdot (-\lambda \nabla T) = Q, \tag{1}$$

where T is the temperature as a dependent variable, ρ is the density of porous media, C_p is the specific heat capacity, λ is the thermal conductivity, t is the time, and Q is the heat source.

The following Richard's equation, which is applicable for an unsaturated and saturated flow in porous media, is used in the Subsurface Flow Module:

$$[C + S_e S]\frac{\partial H_p}{\partial t} + \nabla \cdot [-K\nabla(H_p + D)] = Q_s, \tag{2}$$

where H_p is the pressure head as a dependent variable, S is the storage coefficient, C denotes specific moisture capacity, S_e is the effective saturation, K is the hydraulic conductivity, t is the time, D is the elevation, and Q_s is the mass source. The specific storage is set as follows:

$$S = \rho_f \cdot g(x_p + \theta x_f) \tag{3}$$

where ρ_f is the fluid density, g is the acceleration of gravity, and x_p, x_f is the compressibilities of the solid particles and fluid, respectively. The hydraulic conductivity is

$$K = K_w^{sat} . K_r, \tag{4}$$