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Hydro-mechanical modelling of swell behaviour of bentonite buffer

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Compacted bentonites are often considered as the buffer material in constructing Deep Geological Repositories (DGR). Bentonite buffer exhibits volume expansion when it comes in contact with water. During saturation, the bentonite swells and generates swell pressure. In a DGR, the swell pressure of bentonite buffer gets generated when the voids formed due to temperature fluctuations are sealed due to closure of voids [1]. The temperature changes in the DGR alter the important hydraulic characteristics of compacted bentonites (i.e., permeability and water retention). The permeability and water retention parameters are crucial to anticipate the hydration rate of the buffer and resulting changes in the swell pressure of the buffer [2]. So, the mechanical response of the buffer (i.e., swell pressure), which is crucial for the performance assessment of the buffer, needs to be investigated by considering temperature-induced changes on the water retention behavior. So far, many numerical models have been developed to capture the swell response of bentonite [1,3]. But very few studies considered the changes in hydraulic parameters of soil subjected to different temperatures and, thereby, their effect on the mechanical behavior of the buffer [2]. Therefore, in the current work, a hydro-mechanical model was developed to assess the swell pressure of the buffer by incorporating the temperature influence on the water retention behavior of bentonite. The simulations were performed for three different constant temperature cases of 20ºC, 40ºC and 60ºC.

The governing differential equations of the Hydro-Mechanical (HM) model were acquired from the past study to investigate the influence of temperature on bentonite buffer's swell pressure [1]. Richard's fluid flow equation was utilized for capturing the system of two-phase fluid flow (i.e., water and air) in the soil pores. The primary variable in Richard's equation is fluid pressure, and the secondary variables are the degree of saturation and permeability of fluid. The negative pressure head from the in Richard's equation indicates the suction and positive pressures head implies pore pressure. The van Genuchten relative permeability model was adopted to relate the suction and degree of saturation. The Extended Barcelona Basic Model (BBMx) elasto-plastic mechanical constitutive model was coupled with the changes in the suction with the fluid flow [3]. In this formulation, the hydraulic and mechanical processes are coupled by updating the suction values in the mechanical constitutive model at each time step.

The present work considers a 2D axisymmetric geometry with dimensions of 0.05 m (Diameter) and 0.012 m (Height) [2]. Febex bentonite compacted at dry density of 1.65 Mg/m^3 was considered for the simulations under constant volume conditions (i.e. confined in all the directions with roller boundaries). The fluid flow in the sample occurs due to atmospheric pressure condition at the bottom boundary, whereas the other boundaries were under no flux condition. The mechanical parameters of the BBMx constitutive model were calibrated from the experimental study of Lloret et al. [4]. However, the temperature influenced hydraulic parameters were evaluated from the experimental investigations of Villar & Lloret [2]. The initial suction of the samples subjected to constant temperatures of 20, 40 and 60ºC are 170, 160 and 130 MPa respectively [2]. From the experimental observations, the soil-water retention curve parameters of the compacted bentonite samples at all constant temperatures were determined. Thereby, the model explicitly incorporated the effect of temperature on the swell behavior of bentonite from the altered water retention parameters. The simulations of all three test cases were performed for the time duration of 30 days. The swell pressures were reported as the surface average values over the sample geometry. The current model did not consider changes in the viscosity and density of the water with temperature and the temperature induced strains.

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The calibrated van Genuchten fitting parameters (α – fitting parameter and n – pore size distribution parameter) at different temperatures are detailed in Table. 1. From the study, it was observed that, at high temperatures, the bentonite's water retention parameters were altered (α and n). The van Genuchten fitting parameter (α) was higher for the sample subjected to 60ºC, indicating a lower air entry pressure compared to the sample subjected to 20ºC. Also, a higher value of n for 20ºC sample represents a narrow pore size distribution. Based on the pore size distribution parameter (n), the sample subjected to 60ºC allows a higher water volume into its pores compared to the sample exposed to 20ºC.

After performing the HM simulations with the temperature dependent water retention parameters, it was noted that the variation in temperatures affected the maximum swell pressures of bentonite. The capillary pressure decreased with increased buffer saturation for all temperatures. However, a lower value of suction was observed for higher temperature induced sample (i.e., 60ºC) at a particular saturation compared to other samples. The lower capillary pressure at higher temperatures could be substantiated from Tang and Cui's past study [5], where interfacial tension decreases as a result of increase in temperature. Because of the lower suction at higher temperatures, the maximum swell pressure was observed to be higher for the sample exposed to 60ºC (Fig.1). In addition, as the sample subjected to higher temperatures has lower value of n, it suggests that the soil has a broad range of pore sizes. The presence of broad range of pore sizes allows additional embedding of water molecules into the interlayers of bentonite. Therefore, the samples subjected to high temperatures adsorbs more water into the interlayers and there by repulsion of diffuse double layer resulting in high swell pressures (Fig.1).

Table 1: van Genuchten fitting parameters at different temperatures

Temperature (ºC)	α (1/m)	n (-)
20	1.83×10^{-4}	1.59
40	3.38×10^{-4}	1.36
60	5.86×10^{-4}	1.29

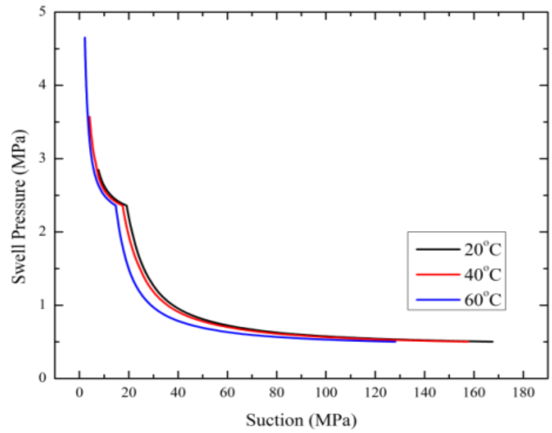

Figure 1: Hydro-mechanical response of bentonite at different temperatures

Overall, the simulations suggest that for possible confined conditions inside a DGR, the effect of temperature on the hydro-mechanical response of the buffer depends on water retention behavior of buffer. Therefore, further modelling studies are needed on the water retention behavior of buffer at high temperatures (i.e., 80 ºC to 200 ºC) that are prevalent in DGR. These modelling studies will help in understanding the long-term performance of the buffer inside the DGR.

Contributor statement

Nandini Adla. developed the numerical model, the mathematical framework and wrote the abstract; Pavan Kumar Bhukya developed the numerical model and edited the abstract. Dali Naidu Arnepalli supervised the work, reviewed and edited the abstract.

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