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Modelling in the frame of hydro-mechanical infiltration column experiment to study the behaviour of binary mixtures of bentonite MX80

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Binary mixtures of high-density MX80 bentonite pellets (80% mass ratio at a dry density of 2.0 Mg/m^3) and powder (dry density of 1.1 Mg/m^3) at hygroscopic water contents are studied by the French Institute of Radiation Protection and Nuclear Safety (IRSN) as an alternative in engineered barrier systems for the long-term disposal of radioactive wastes. The MX80 bentonite was studied by many authors [1–4] with this aim. These mixtures show a dry density around 1.49 Mg/m^3 on pouring into infiltration column experiment tests.

An infiltration column cell (100 mm in diameter and 350 mm high) has been developed at a reduced scale of 1/100 of the VSS (i.e., at 1/10 of the in situ VSEAL test) to reproduce asymmetric hydration using independent top (fast injection) and radial (slow injection) water pressure systems, which will undergo fast hydration from the calcareous Oxfordian formation at the top and a slower one by water reaching radially through the Callovo-Oxfordian formation. It also allows performing gas injections at different locations of the core of the bentonite mixture (top and bottom boundaries) and under various hydraulic states. The infiltration column is composed of four transparent cylinders, made of Perspex to visualise processes occurring at the interface during the hydration and gas injection phases (Figure 1a). This cell has been assembled with three stainless-steel injection rings that ensure slow radial water injection through three independent automatic pressure/volume controllers. These stainless-steel injection rings also hold the different lateral transducers (six total stress cells and three water pressure transducers embedded in the soil and three relative humidity probes installed in small dismountable chambers) (Figure 1a). The assembled cell is inserted into a rigid frame composed of two stainless steel disks on the two sides of the cylinder connected by four metallic rods.

A numerical model has been developed to better understand the coupled hydro-mechanical response of this multi-porosity mixture and particularly of its constitiuents upon hydration.The characterisation of pellet and powder components have been focused on their water retention properties, water permeability, compressibility on loading and on suction changes, as well as on their swelling pressure response and the progressive changes of their pore size distribution on wetting. This information at component scale has allowed the upscaling into a 2D plane-strain numerical model based on the discretisation of pellets and inter-pellet powder using Code_Bright FEM [5]. This plane-strain model captures the pellet shape effect without changing the geometry of the pellets.The geometry used in the simulations corresponds to an infiltration column at constant volume mimicking the actual asymmetric hydraulic conditions of the VSS. Figure 2b presents the geometry of the model used at constant volume based on the discretisation of pellets and powder (252 pellets of 8 mm diameter and surrounded by powder filling the entire inter-pellet volume).The generated numerical mixture has a mass-basis proportion of 77.6% pellets and 22.5% powder, which is close to the mixture proportion. Figure 1b shows the three lateral slow-rate hydration boundaries, as well as the fast-rate hydration boundary at the top. The modelling has focused on analysing the global and particularly the local responses: water mass transfer between powder and pellets, evolution of local degrees of saturation and porosities (inside pellets and powder), and mean stress evolution in the pellet and powder domains. Water retention and permeability properties of the components are dependent on porosity and the degree of saturation.

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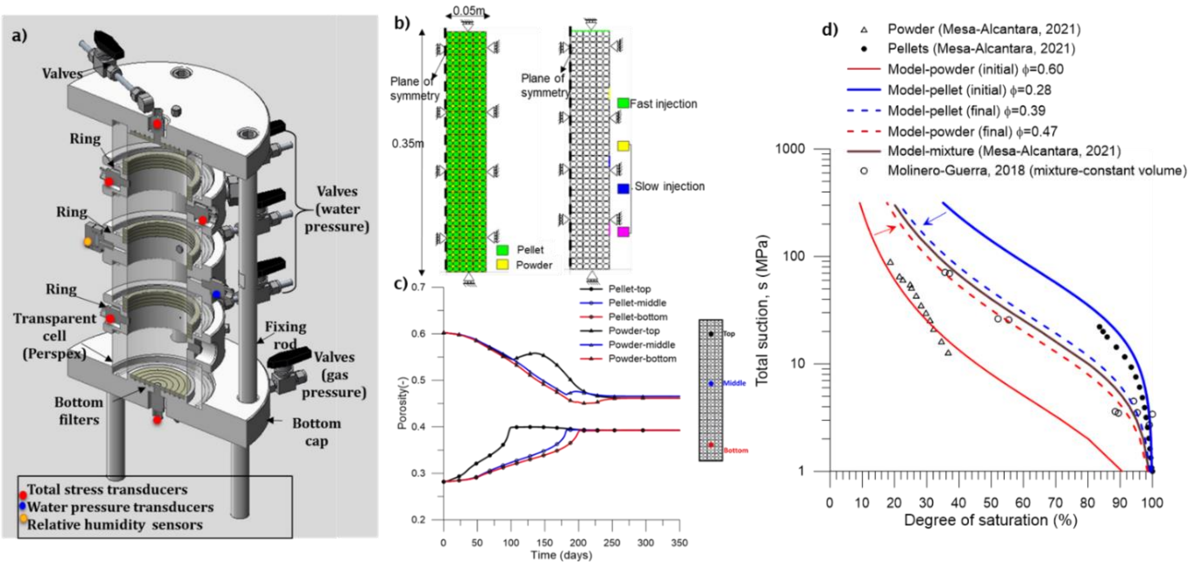

Figure 1: a) Infiltration column with auxiliary, b) Material, geometry, mesh and boundary conditions, c) Porosity evolution at different elapsed times for the powder and pellets d) Evolution of the total suction of pellets and powder during hydration.

A non-linear elastic model has been considered for the components, in which volumetric deformations are induced by net mean stress and suction changes. Therefore, the pellets and powder have different hydraulic and mechanical properties as a consequence of the different initial properties, but they share the same constitutive relationship of a single structured material. Figure 1c presents the time evolution of porosities (inside the pellets and powder), showing that the mixture tends towards a more homogeneous distribution of porosity as the pellets expand and compress the highly deformable clay powder. During the transient hydration stage, the expansion of pellets at the top of the column evolves faster due to the proximity of the hydration front. Figure 1d shows the water retention curves of the pellets and powder at the initial state and after hydration as predicted by the model, compared to experimental data [6,7]. The predicted water retention curves of the pellets and powder adequately follow the trend of the data reported by [7] and also seem to reproduce the mixture model data suggesting a homogenisation of the retention properties of the material after hydration.

Contributor statement

AMA: Conceptualisation, Methodology, Formal analysis, Investigation, Visualization, Writing-Original Draft.
ER: Conceptualisation, Methodology, Funding acquisition, Supervision, Resources, Validation, Writing - Review & Editing.
NM: Conceptualisation, Funding acquisition, Supervision, Validation, Writing - Review & Editing.

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