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Hydro-mechanical constitutive model for unsaturated compacted bentonite–sand mixture (BSM): Laboratory tests, parameter calibrations, modifications, and applications

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ABSTRACT

A bentonite–sand mixture (BSM) is one of the clay-based sealing components proposed for use in a Canadian deep geological repository (DGR) for used nuclear fuel. Numerical modelling to assess the overall design of the proposed DGR requires characterisation of the hydraulic–mechanical (H–M) of each of the components of the sealing system, including the BSM. The BSM currently under consideration is a 50/50 mixture (by dry mass) of bentonite and well-graded silica sand, compacted to a dry density of at least 1.67 Mg/m^3. This paper presents the H–M constitutive model parameters, calibrated for BSM specimens under saturated and unsaturated conditions, based on various laboratory tests. A set of parameters for an elastoplastic model for unsaturated soil, Basic Barcelona Model (BBM), have been determined to simulate the mechanical behaviour of the BSM specimen. A set of parameters for van Genuchten's Soil–Water Characteristic Curve (SWCC) and Kozeny's hydraulic permeability model have been determined to simulate the hydraulic behaviour of the BSM specimen. Using a finite element computer code, CODE_BRIGHT, these sets of parameters have been used to simulate H–M processes in BSM specimens during water infiltration under constant volume (CV) and constant mean stress (CMS) boundary conditions. The key features of the selected constitutive models that are different from the laboratory tests of the BSM specimen have been summarised. The functions to improve the capability of the selected constitutive models to match the laboratory test results of the BSM specimen have been proposed.

1. Introduction

A compacted bentonite–sand mixture (BSM) is one of the clay-based sealing components proposed for use in a Canadian deep geological repository (DGR) for used nuclear fuel (Maak and Simmons, 2005). Numerical modelling to assess the overall design of the proposed DGR requires characterisation of the hydraulic and mechanical (H–M) behaviour of this clay-based sealing material. Other effects (e.g., thermal or chemical) on the behaviour of the clay-based sealing material are also important, but this paper will be focused on the H–M aspects.

The BSM considered is a 50/50 mixture (by dry mass) of bentonite clay and well-graded silica sand, compacted to a dry density of at least 1.67 Mg/m^3. A number of laboratory tests to investigate the H–M behaviour of BSM specimens have been completed under both saturated and unsaturated conditions (e.g., Dixon, 1995; Wiebe, 1996; Tang, 1999; Blatz, 2000; Anderson, 2003; Siemens, 2006). These laboratory test results were used to calibrate the H–M constitutive model parameters of a BSM specimen under unsaturated conditions. The 50/50 BSM has been the focus of this study due to the extensive data base to support assessment of more rigorous H–M constitutive models for unsaturated soil (e.g., the Basic Barcelona Model (BBM) (Alonso et al., 1990)).

The objectives of this paper are to: (1) calibrate the H–M constitutive model parameters based on various laboratory test results; (2) demonstrate the application of these H–M constitutive model parameters to simulate the H–M behaviour; and (3) identify the difference between the selected H–M constitutive model features and the laboratory test results of the BSM specimens under unsaturated conditions.

In order to address the first and second objectives, H–M constitutive models used in the finite element computer code were also used in the calibration process. The parameters of an elastoplastic model for unsaturated soil, the BBM (Alonso et al., 1990), were determined to simulate the mechanical behaviour of the specimen. The parameters of the Soil–Water Characteristic Curve (SWCC) of the van Genuchten (1980) and Kozeny's permeability model were determined to simulate its hydraulic behaviour. Using a finite

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element computer code, CODE_BRIGHT, these sets of parameters were used to simulate H–M processes of a BSM specimen during the infiltration process under constant volume (CV) and constant mean stress (CMS) boundary conditions. The numerical modelling results were then compared with the laboratory test results.

The calibration of the constitutive model parameters was done by matching the laboratory test results with the constitutive model results. This matching was not always possible using a unique set of parameters for the following reason. A constitutive model was usually developed for a particular type of material. When it was used for different material, the formulation of the constitutive model was only valid within a limited range of stress state variables. Based on the results obtained during the calibration process and numerical modelling of the BSM specimens, the features of the selected constitutive models that were different from the laboratory tests of the BSM were identified. Finally, based on these differences, some functions to improve the capability of the selected constitutive models to match the laboratory test results of the BSM specimen were defined.

2. Hydraulic constitutive model

Both H–M constitutive models are required to simulate the behaviour of the BSM specimen. This section presents the calibration of the hydraulic constitutive model parameters of the BSM specimens.

2.1. Van Genuchten and Kozeny's equations

The SWCC defines the relationship of the degree of saturation (S_w) and suction (s). The SWCC used in this paper is based on the van Genuchten (1980) model and described as follows:

$$s = P_0(S_e^{-1/a} - 1)^{1-a} \quad (1)$$

$$s = u_a - u_w \quad (2)$$

where P_0 and a are constant parameters, u_a is pore air pressure; u_w is pore water pressure; and S_e is the effective degree of saturation, which is defined as follows:

$$S_e = \frac{S_w - S_{res}}{S_{max} - S_{res}} \quad (3)$$

where S_{res} is the residual degree of saturation and S_{max} is the maximum degree of saturation.

Unsaturated water hydraulic conductivity (k_w), as a function of S_w, is also based on the van Genuchten (1980) model and defined as follows:

$$k_w = k_{w\text{-}sat} \cdot \left(S_e^b\left[1 - \left(1 - S_e^{1/a}\right)^a\right]^2\right) \quad (4)$$

where $k_{w\text{-}sat}$ is the saturated water hydraulic conductivity. The $k_{w\text{-}sat}$ is dependent on the current total porosity (n), and their relationship is defined using Kozeny's model:

$$k_{w\text{-}sat} = k_0 \frac{n^3}{(1-n)^2} \frac{(1-n_0)^2}{n_0^3} \quad (5)$$

where n_0 is the initial total porosity and k_0 is water permeability corresponds to the initial porosity.

2.2. Bentonite–sand mixture (BSM) specimen

The BSM specimens were compacted to an initial dry density (ρ_{dry}) of approximately 1.67 Mg/m^3 and gravimetric water content (w_c) of approximately 18.75%. The process developed by Yarechewski (1993) was used for compacting BSM specimens without an internal psychrometer or sensor. The uncompacted BSM was preconditioned to achieve the target water content. Triaxial specimens were made by statically compacting this un-compacted material in five 20 mm lifts in a cylindrical mould to create specimens measuring 50 mm in diameter and 100 mm in height. The remaining material was used for a confirmatory water content measurement. This process was modified and used to allow compaction of an internal psychrometer by Blatz (2000) and Xeritron sensor by Siemens (2006).

2.3. Parameter calibration

As defined previously in Section 2.2, the initial target water content and dry density of the BSM specimens are 18.75% and 1.67 Mg/m^3, respectively. Shrinkage tests were used to determine the SWCC during drying (i.e., Wiebe, 1996, Tang, 1999, Blatz, 2000, and Anderson, 2003). Infiltration tests were used to determine the SWCC during wetting (i.e., Siemens, 2006). Fig. 1 shows the data points from shrinkage and infiltration tests and the SWCCs during drying and wetting of the BSM specimens.

In shrinkage tests (Wiebe, 1996, Tang 1999, Blatz, 2000, and Anderson, 2003), the BSM specimens were compacted to initial target ρ_{dry} and w_c. Environments of various relative humidity conditions were created in sealed desiccators using acid or salt

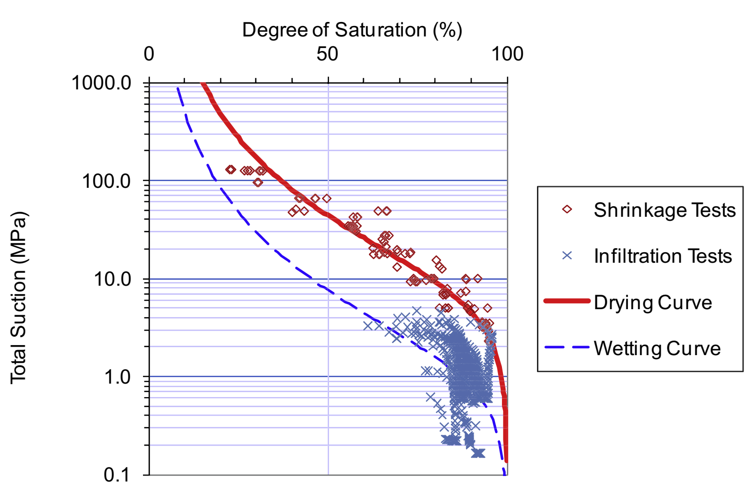

Fig. 1. Soil Water Characteristic Curve for the bentonite–sand mixture specimen.