Double structure effects on the chemo-hydromechanical behaviour of a compacted active clay

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Aim of the study

Experimental and modelling study on the coupled hydro – chemo - mechanical behaviour of saturated compacted bentonites

Chemically induced deformations

Caused by chemical interaction between soil particles and pore water. Cations 'shield' the electrical repulsion occurring between charged clay particles.

>> In suspensions << DLVO theory:

Distance between particles is such that replusion forces (of electrical nature) and attraction forces (van der Waals) come to an equilibrium.



(Mitchell & Soga, 2005)



Increasing concentrations reduce the thickness of the double layer



Volume reduction - shrinkage

Other causes of shrinkage

Shrinkage can be associated to cation exchange.

Sodium or calcium bentonites can 'illitize' when K⁺ atoms substitute other cations in the mineralogic structure

(Mitchell & Soga, 2005)

Homoionic reconstituted clays

'swelling pressure' as the difference between the osmotic pressure in the pore fluid and the osmotic pressure in the central plane between parallel platy particles





"...physico-chemical variables control tendency to disperse or to form aggregates.

"Aggregation \rightarrow many tiny flow channels through which there is likely to be little flow and a smaller number of relatively large channels through which the main flow occurs.

"Dispersion \rightarrow channels all nearly of the same size, and thus reduces the flow"

ESEM evidences of relationship between salinity and structure

FEBEX Bentonite – statically compacted ρ_{d} = 1.65 Mg / m^{3}



a) After static compaction b) After saturation with a 0.5 M NaCl solution c) After saturation with Distilled Water

- Ss: (750 m²/g; 35 m²/g)
- CEC: 106 meq/100 g



Gens & Alonso, 1992; Gerke & Van Genuchten, 1993

Double porosity model

Transport: Barrenblatt, 1960; Warren & Root, 1963; Gerke & Van Genuchten, 1993

Mechanical: Gens & Alonso, 1963



Transport:

Water and solute fluxes occur through the macroporosity and the microporosity domain.

Exchange can occur between the two domains in virtue of potential differences

Double porosity model

Transport: Barrenblatt, 1960; Warren & Root, 1963; Gerke & Van Genuchten, 1993

Mechanical: Gens & Alonso,1992

Mechanical:

The material (overall) and the aggregates deform upon variation of chemical, hydraulic and mechanical stresses.

Transport parameters evolve as well as a consequence of fabric changes





Constitutive variable: osmotic suction

 $\pi = iRTc$ (Van't Hoff)

Chemo – mecanical model

 $d\mathcal{E} = d\mathcal{E}_{M} + \alpha^{*} d\mathcal{E}_{m}$

 dE_M macroporosity strain dE_m microporosity strain $d\epsilon$ overall strain

Mechanical Characterization: micro and overall

Micro behavior

MIP Analyses







(π , osmotic suction)

 $d\epsilon = d\epsilon^{M}_{vol} + \alpha^* d\epsilon^{m}_{vol}$

Model: dotted line

$$d\varepsilon_{vol}^m = \alpha \exp(-\beta \pi_m) d\pi_m$$

Relationship $e - \pi$

Swelling under load, $\sigma_v = 500 \, kPa$



Castellanos et al, 2008

NaCl

▲ CaCl2

- semilog

Relationship $e - \pi$

0

-0.05

-0.1

Swelling upon soaking, load $\sigma_v = 500 \, kPa$

macroporosity changes

$$d\mathbf{E} = \mathbf{d}\mathbf{E}^{\mathsf{M}}_{\mathsf{vol}} + \alpha^* d\mathbf{E}^{\mathsf{m}}_{\mathsf{vol}}$$

By observing that differential microscopic strains tend to disappear at high suctions



-0.2 \square -0.25 -0.3 100 10000 100000 1000 osmotic suction, π (kPa) Macroporosity changes



Salt transport test under oedometer conditions

- 1. statically compacted sample;
- 2. saturation with saline water (NaCl 5.5 m) placed in both reservoirs;
- 3. distilled water in the lower reservoir;
- 4. monitoring vertical displacements and concentration in the 'free' reservoir





FE simulation with a commercial software (Comsol): Mechanical strains: as introduced (... $d\epsilon^{M} = k_{\pi}/\pi_{M} \cdot d\pi_{M} - k_{p}/\sigma \cdot dp_{M})$ Transport model (water phase):

$$\frac{\partial(\phi_{m})}{\partial t} - q_{w}^{EX} = 0 \qquad \qquad \omega : Bresler (1972)$$

$$\frac{\partial(\phi_{M})}{\partial t} + \nabla \cdot \left(-\frac{K_{M}}{\rho_{f}g} \nabla(p_{M}) + \omega \frac{K_{M}}{\rho_{f}g} \nabla(\pi_{M}) \right) + q_{w}^{EX} = 0$$
Transport model (salt mass):
$$\frac{\partial(c_{m}\phi_{m})}{\partial t} - \left(q_{s}^{EX} \right) = 0$$

$$\frac{\partial(c_{m}\phi_{M})}{\partial t} + \nabla \cdot \left(c_{M}\mathbf{q}_{M} (1 - \omega) - \phi_{M} (1 - \omega) p_{M0} \nabla c_{M} \right) + q_{s}^{EX} = 0$$
Coupled transport, satisfies Onsager reciprocity

Exchange term: $\mathbf{q}_s = \chi (\mathbf{c}_M - \mathbf{c}_m) \rightarrow \chi = \mathbf{f}(\mathbf{e}_m)$ non linear, similarly to Gerke & van Genuchten (1993)



Calibration of the osmotic efficiency parameter ω : Bresler (1972)







Trasporto Macro

Conclusions

- 1. Double structure and its evolution documented through MIP and ESEM
- 2. Characterization:

micro through MIP results
macro through oedometer tests (swelling + mech loading)

- 3. Consistent reproduction of a salinisation desalinisation test (coupled transport within the macro)
- 4. Non linear exchange term:

deformations with 'jumps' upon swelling, continuous upon compression

differences in swelling and compression times

Comparison of models: concentration



Comparison of models: displacements



Reconstituted materials, permeability

Calvello et al., 2005, campioni ricostituiti di Argilla di Bisaccia

