Poster [GGET]

Geomechanics / Geophysics / EDZ / THM
A MULTISCALE APPROACH FOR THE HOMOGENIZATION OF CLAY MATERIALS

Christian Moyne 1, Thibault Lemaire 1, Didier Stemmelen 1, Márcio Arab Murad 2

1. LEMTA, UMR 7563 CNRS-INPL-UHP, 2 avenue de la Forêt de Haye, B.P. 160, 54504 Vandœuvre-lès-Nancy, France
2. Laboratório Nacional de Computação Científica LNCC/MCT, Av Getúlio Vargas 333, 25651--070 Petrópolis, RJ, Brésil

Smectitic clay mineral is a 2:1 layer composed of an octahedral aluminia sheet sandwiched between two silica tetrahedral sheets forming an unit layer. The units are stacked together to form what is known as the crystal lattice. An important property of the clay minerals is the negative charge of their surface due to isomorphic substitutions of certain atoms of their structure. To achieve a global electroneutrality condition, this charge is balanced by a positive cloud of positively charged counterions located in the electrolyte aqueous solution externally to the crystal forming the so-called electrical double layer. The aim of this presentation is to derive a macroscopic model for highly compacted expansive clays based on a rigorous scale-up procedure and capable of establishing a precise correlation between the macroscopic parameters and microscopic chemo-electro-hydrodynamics.

At the microscopic scale the clay material composed of a solid phase with an uniformly negatively charged surface and a liquid one. For simplicity the liquid phase is considered a mixture of water and ions of an entirely dissociated monovalent salt. The electric potential is given by the Poisson equation. The movement of the fluid phase (assumed newtonian) is given by the Stokes equations supplemented by an electric force term. The movement of the ions is due to a convective movement and a diffusion one. The diffusion term is the sum of a fickian term and a forced diffusion one accounting for the effect of the electric forces acting on the ions. The solid phase is supposed to be isotropic elastic.

The homogenization technique is applied to propagate information available in the pore-scale model to the macroscale. Assuming local periodicity, we derive macroscopic equations via formal application of matched asymptotic expansion techniques. At the macroscopic scale the following equations are derived:

- a Poisson - Boltzmann equation (at the microscopic scale) for the double layer potential,
- a Darcy modified equation supplemented by both a chemical osmosis term induced by a salt concentration gradient and an electro-osmotic term induced by a streaming potential gradient,
- two convection-diffusion equations for the cations and anions transport; alternatively these equations can be put in the form of a salt transport equation and a (electrical) charge conservation equation,
- biot poroelasticity equations with a Terzaghi principle modified by an additive "swelling pressure term" to incorporate the physicochemical effects.

References


EVALUATION OF CRUSHED CLAY ROCKS AS A FILLING MATERIAL FOR WASTES STORAGE GALLERIES

Jean-Marie Fleureau 1, Arézou Modaressi 1, Muzahim Al-Mukhtar 2, Luc Deroo 3, Odile Ozanam 4

1. Laboratoire MSS-Mat, Ecole Centrale Paris & CNRS, Châtenay-Malabry
2. CRMD, CNRS & Orleans University, Orléans
3. ISL Consulting Engineers, Paris
4. Service Géomécanique, Andra, Châtenay-Malabry

In order to ensure the long-term mechanical stability of nuclear wastes storage galleries and wells, the use of a filling material is considered. As large quantities will be necessary, the material must be inexpensive and available near the excavation site. Its properties must be sufficient to resist the high stresses at a 500 m depth, assuming that, in the long term, the strength of the concrete used in the retaining structures may be drastically reduced. However, the aim of the filling material is not to directly ensure the confinement of nuclear wastes, that will be done by swelling clay engineered barriers.

In this paper, the properties of the argillaceous rock from the Meuse - Haute Marne site of Andra underground laboratory are studied. In order to take into account the vertical variability of this material through the layer, two materials 'samples' have been made: the first one from rock samples cored at depths above the future excavated galleries level (between 477 and 493 m) and the second one at depths below the future excavated galleries level (between 493 and 515 m), corresponding respectively to the geotechnical levels C1 and C2, as defined by the geological reference study for this French site.

Both materials are crushed, using a standardised procedure, to obtain 2 classes of grain size distributions, one with grains smaller than 1 mm, the other one with grains smaller than 16 mm.

Several tests are carried out to estimate the properties of the materials compacted to the standard Proctor optimum water content and maximum density, or to conditions corresponding to approximately 95% of Proctor maximum density and several water contents. The strength of the compacted materials is estimated using a standardised test called CBR, that consists in measuring the force necessary to drive a cylinder into the material to a given depth. Compressibility tests are also performed in oedometers on the materials in their unsaturated state, up to stresses of 10 MPa.

The influence of water on the materials was carefully considered, as these rocks may sometimes disperse in water very easily and quickly. To that effect, swelling tests on compacted specimens, dispersion tests on natural and compacted specimens, collapse tests on specimens under stress are carried out, either using pure water, water vapour or water previously equilibrated with the material.
In order to interpret the data, mechanical and physico-chemical characterisation tests are made, using several different methods: grain size and mineralogy analyses, measurement of Atterberg limits, X-ray diffraction, mercury intrusion, etc.

At the same time, an investigation of the methods that could be used to lay and compact the material in the galleries, based on available literature, is carried out.

In conclusion, the aim of this study was to assess the possibility to use the material excavated from the site itself to fill it again after a storage period corresponding to the period of activity of the storage. The available data indicate that additional work will be necessary to optimise the grain size distribution of the material used, analyse the consequences of its susceptibility to water and possibly improve its mechanical properties.
DESIGNING OF SOIL - MIXTURE BARRIERS: APPLICATION OF CONSOLIDATION TESTS

Beata Łuczak-Wilamowska, Paweł Dobak

Faculty of Geology, Warsaw University, Żwirki i Wigury 93, 02-089 Warszawa, Poland, e-mails: blw@geo.uw.edu.pl, pdobak@geo.uw.edu.pl

Soil mixtures consisting of impermeable clays and permeable sands are considered for forming of soils barriers in waste disposals. The idea of addition of sand to the clayey soil arose from the necessity of obtaining proper strength of soils. Estimation of filtration parameters is difficult because modeling of seepage in these soils takes much time. Application of consolidation theory is a useful method of evaluation of filtration process in an impermeable soil environment. The best method of the evaluation of seepage parameters is the continuous loading in consolidation tests (CL). Systems of CRL (constant rate of loading) and CRS (constant rate of strain) let obtain results in short time. In the steady phase of test, the coefficient of permeability is stabilized, too. The basic formula of the evaluation of the coefficient of permeability is:

\[
k = \frac{c_v \cdot \gamma_w}{M_k} \cdot \frac{\Delta\sigma - \Delta\sigma'}{2 \cdot \Delta t \cdot u_b \cdot \Delta h},
\]

where:

- \(c_v\) – coefficient of consolidation
- \(\gamma_w\) – unit weight of water
- \(M_k\) – modulus of compressibility
- \(\Delta\sigma\), \(\Delta\sigma'\), \(\Delta h\) – increment of: total stress, effective stress, height of sample in elapsed time \(\Delta t\)
- \(H\) – way of drainage
- \(u_b\) – pore water pressure at impervious base

Coefficient of consolidation \(c_v\) is evaluated from the distribution of pore water pressure and from changes in height of the soil specimen. Values of pore water pressure depend on granulation, which is related to permeability. Two types of the distribution of pore water pressure were observed in consolidation tests (Figs. 1, 2, symbols as in Fig. 3). The pressure of pore water increases continuously in natural clays. In soil mixtures we observed an increase of pore water pressure at the initial stage of tests and its subsequent stabilization or decrease. This effect shows that the steady phase of CL-consolidation is achieved in soil mixtures. The mechanism of seepage in soil barriers can be described basing on comparison of theoretical and experimental distribution of pore water pressure. Proper forming of a mineral barrier is necessary to obtain semi-impermeable layers.

![Fig. 1.](image1.png)

![Fig. 2.](image2.png)
The relationship between the coefficient of consolidation and the void ratio can be used to evaluate a suitable compaction. Various relationships between permeability and composition of soil-mixtures are shown in the Fig. 3 (M20s: 80% clay+20% sand). The addition of sand makes the soil's permeability very sensitive to the degree of compaction. The main problem in construction of a barrier layer is the choice of the appropriate content of sand, by which the soil would remain impermeable and the shear strength of soil would be sufficient for safety of waste disposal. CL tests of consolidation let obtain different, multidimensional connections between permeability and parameters of compaction of barrier layers. A variety of compositions of soil-mixtures may be tested by CL method with application of different boundary conditions, especially the velocity of loading, straining and increasing pore water pressure.

![Coefficient of permeability vs. Void ratio](image)

**Fig.**

- Black clay
- Brownish-grey clay
- Brown clay
- M20s
- M40s
- M60s
- M80s

Extrapolated values of k by $e_{min}$
MICROMECHANICAL MODEL FOR COMPACTION CHARACTERISTICS OF BENTONITE - SAND MIXTURES

Y. M. Tien ¹, P. L. Wu ¹, W. S. Chuang ², L. H. Wu ²

1. Department of Civil Engineering, National Central University, Taiwan, ymt@cc.ncu.edu.tw
2. Institute of Nuclear Energy Research, Atomic Energy Council, Taiwan

It is generally considered that compacted bentonite-sand mixtures will possess higher structural integrity, higher thermal conductivity, and higher stiffness than pure bentonite. When combined in optimum proportion bentonite-sand mixtures can form an excellent engineering barrier that is dimensionally stable and possess a low value hydraulic conductivity. Buffer materials made of bentonite and silica sand or crushed rocks are the candidate of buffer materials in many countries’ concepts of the geological disposal for high-level radioactive waste. Bentonite-sand mixtures are comprised of two truly contrasting geomaterials in regards to grain size, physical and chemical properties. Compaction characteristics of a bentonite-sand mixture are highly dependent on sand content and compressibility of pure bentonite. This paper is mainly focused on the compaction characteristic of bentonite-sand mixtures with varied sand content from the experimental and theoretical point of view. To examine the effect of sand content, a series of uniaxial compaction tests for bentonite-sand mixtures with different sand content were performed. In addition, a compaction model based on micromechanics for bentonite-sand mixtures was proposed. The applicability of the proposed model was examined and validated by using experimental data. Figure 1 shows a comparison between the experimental and predicted compaction stress vs. overall dry density of bentonite-sand mixtures. Figure 2 shows a comparison between the experimental and predicted rebounded constrained modulus vs. overall effective clay dry density of bentonite-sand mixtures. They can be seen that the proposed model based on micromechanics can predicted reasonably well the compaction characteristics of bentonite-sand mixtures both in loading and unloading stages.
Experimental data
Bentonite content, %
- 100%
- 85%
- 70%
- 60%

- predicted by proposed model

Fig. 1: Comparison of experimental and predicted compaction stress – overall dry density of bentonite – sand mixtures

Experimental data
Bentonite content, %
- 100%
- 85%
- 70%
- 60%

- predicted by proposed model

Fig. 2: Comparison of experimental and predicted rebounded constrained modulus
Bentonite is a composite mudrock, which mainly composed of montmorillonite and other minerals (quartz, feldspars, mica, carbonates and heavy minerals). Granulometric composition is one of the most important characteristic features of barrier materials in many respects determining their physic-chemical properties (porosity, pore size, penetrability, density, moisture retention and other characteristics of materials). Lately, the fractal geometry tenets are used more and more frequently for describing porous and solid phases of soils. The role of fractal nature of an aggregate of particles and their surface in radionuclides and heavy metals sorption processes gives no rise to doubts.

Okhotin [1] has shown that the smallest porosity of dispersed substances is available when each subsequent fraction’s diameter is sixteen times smaller than that of the previous one and the ratio of their weight contents is 3/7. In the 3 or 4 fractions mixtures it was succeeded to decrease porosity to 4–5 %. Such system of particles was shown to have the following fractal dimension D = 2.67 ± 0.02. Fractal dimensions were calculated by regression equation connecting mass logarithm accumulation curve (lg Q) with particles radius logarithm (lg r). The justified dispersion share of the obtained values was R = 0.997 with the regression amount Fisher criterion as $F_k = 1810.8$. The aggregate in which the smallest particles were 10 orders smaller than the biggest ones was studied. In nature such mixtures are very rare since the porosity of natural objects is rarely lower than 25 - 27 %.

When studying fractal dimension of dispersed materials used for geochemical barriers construction, it was shown that fractal dimension of particles aggregate composing these materials varies in wide range, for example bentonite particles aggregate fractal dimension from Cherkassy deposit was $D = 1.74 \pm 0.31$, with $R = 0.94$ and $F_k = 118.6$. Many dispersed materials were shown to exhibit multyfractality of particles’ system. For example, when studying fractal dimension of kaolinite particles by sedimentation methods, two fractal sub-systems with $D_1 = 2.15 \pm 0.15$ when $R = 0.93$ and $F_k = 141.9$ and $D_2 = 0.44$ when $R = 0.69$ were singled out.

When analyzing the particles size distribution curve by conductometric analysis, the multifractals are observed more clearly along the bend in the 2 μm area of the direct dependence of lg Q on lg r. Particles aggregate in higher-dispersed radii range was found to compose fractals with the dimension equal to 1.44 - 1.89. This range comprises 43 - 86 % of mass share of substance. The bigger particles are aggregates often joined at basic planes and having noticeably higher fractal dimension (from 2.59 to 2.74) with justified dispersion range from 0.87 to 0.9. The specific feature of clayey particles is plain shape. When calculating clayey particles surface fractal dimension basing on the results of comparing of specific surface (method) with electron-microscopic measurement data, it was found that fractal dimension differ in various directions of particles. For example, kaolinite particles fractal dimension was $D = 1.91 \pm 0.39$ with $R = 0.81$ by length and $D = 1.94 \pm 0.31$ with $R = 0.88$ by width. Fractal dimension by thickness is not cited since it has low justification factor values ($R = 0.52$).
If area size of coherent dispersion along the normal towards basic plains calculated by widening of roentgen diffraction lines by quaternary central moments method is used as the parameter on which the kaolinite specific surface depends, than particles surface fractal dimension is $2,25 \pm 0,13$ with $R = 0,92$.

Thus, complicated nature of surface fractal structure and dispersed mineral substances particles aggregate used for barrier materials was shown. More dense packing can be realized when forming the frame of porous structure not by crystalline minerals but by artificially created proportions of isometric aggregates particles, the size of which covers 3 to 4 and more orders of magnitude.

References
CHEMO - MECHANICAL INTERACTIONS IN CLAY: ARE THE ATTERBERG LIMITS USEFUL?

R. Schmitz¹, S. Hiligsmann¹, C. Schroeder¹, J.C. Verbrugge², R. Charlier¹

¹. Université de Liège, Département GéomaC, Chemin des Chevreuils 1, 4000 Liège, Belgique
². Université Libre de Bruxelles

The long-term mechanical and hydraulic behaviour of natural or engineered clay barriers may be modified due to interactions with various chemical or biochemical materials. However, it is very complex to analyse such interactions in the laboratory, and quite impossible in situ. Due to the very low permeability of clay used as seepage barrier, mechanical tests like oedometer tests or triaxial compression tests as well as permeability tests may take a very long time, up to some months or some years. Therefore it would be very useful to have some more time efficient procedures to obtain a first evaluation of potential interactions with various pollutants.

Among some few others tests, the evaluation of the Atterberg limits is a very basic test allowing a first insight into the chemical reactivity of clays. Basically, the liquid limit and the plasticity index are highly and mainly influenced by the ability of clay minerals to interact with liquids (cf. double layer theory).

Based on that idea, it was decided to tests the interactions of some clays with various chemical compounds using the Atterberg liquid limit and plasticity index. The considered clays are three natural Tertiary clays obtained from Belgian quarries, and one mono-mineral clay. Chemical aggression is provided by the addition of: saturated or non-saturated salt solutions, leachates obtained at three domestic waste disposal sites, and demineralised water. The natural clay with its genuine fluid phase presents the reference state. Various conditions of interaction are considered: maceration at different water contents and at various temperatures.

Depending on the association of clay and fluid, different effects may be observed. At the upper limit, pure clays in contact with saturated salt solution show a dramatic change in Atterberg limits. Literature sources show that in such cases, the mechanical behaviour may be highly modified. Atterberg limits seem therefore to be a valuable tool for the detection of chemo-mechanical interactions. Contrary, at the lower limit, no modification of the Atterberg limits may be observed. This is confirmed by a mechanical behaviour that seems not to be influenced by clay - leachate contact. Between these limits, various degrees of sensitivity have experimentally been discerned.

Finally, for some cases with high variations of the Atterberg limits, XRD clay mineralogical analyses have been performed and dominant processes like e.g. illitisation have been identified.
MEASUREMENT OF VERY LOW PERMEABILITIES: COMPARISON OF METHODS AND FIRST RESULTS ON ARGILLACEOUS ROCKS

Jean-Marie Fleureau ¹, Said Taibi ², Cécile Coll ³

1. Laboratoire MSS-Mat, Ecole Centrale Paris & CNRS UMR 8579, Châtenay-Malabry, fleureau@mss.ecp.fr
2. Laboratoire Mécanique, Faculté des Sciences & Techniques, Université du Havre, Said.Taibi@univ-lehavre.fr,
3. Laboratoire 3S, CNRS, INPG & Université Joseph Fourier, Grenoble, Cecile.Coll@inpg.fr

(GdR FORPRO)

The communication sums up the advancement of the benchmark on the hydraulic characterisation of media of very low permeability, co-funded by CNRS and ANDRA, in which 13 research laboratories take part. The first part of the study concerns a model material, a microporous mortar, the conditions of manufacture of which were well controlled, so that all the teams have a reference material of low permeability which is simpler than argillaceous rocks. In the second phase, which is still under way, the comparison will be made on undisturbed specimens of argillaceous rocks from the Andra underground laboratory site. The main objective of the benchmark is to compare measurement techniques and experimental protocols.

Different aspects are studied:
- the comparison of the techniques and devices to measure monophasic permeabilities in saturated samples, developed in the different laboratories. The methods are sometimes very different, but a standard protocol has been adopted to permit their comparison,
- the use of various physico-chemical techniques to characterise the porous space, in order to interpret the results of the permeability measurements,
- the influence of the loading conditions on the permeability of the specimens. The first stage mainly consists in a study of the role of the isotropic stress but the effect of a deviatoric stress is also considered. This last aspect is extremely important insofar as the creation of cracks drastically modifies the conditions of water flow in the material.

Good agreement in the values of the water permeability coefficients measured on the porous mortar in the different laboratories is observed, despite:
- the use of very different techniques, whose interpretation can be rather complex (harmonic method or radial injection, for example),
- the variability of the specimens and the heterogeneity of the material which results in an increased scattering of the measures as the size of the samples decreases,
- the use of tap water, whose chemical composition can be variable from a place to the other (in one case, for example, an evolution of the permeability with time has been observed during tests of long duration, whereas this phenomenon has not been noted elsewhere).

In the case of tests using similar techniques and samples of the same size, the measured permeability coefficients are totally comparable. In the same way, two measurements with ethanol on samples of the same size are perfectly coherent. Tests with gas, on dry samples led to permeabilities of the same order of magnitude.
In most tests, measurements have been made under several isotropic effective stresses, slightly different from a laboratory to the other. The results show that, globally, the changes in permeability remain limited and the absence of trend seems to indicate that it is mainly due to experimental problems and not to the behaviour of the mortar.

The influence of deviatoric stress is often linked to a damage of the material and to the creation of a network of more or less continuous microfissures. This phenomenon plays a major role in the evaluation of the transportation phenomena susceptible to occur in the porous medium. It is why it has been decided to approach it from the first phase of the project. Tests have been performed in a triaxial cell in which confinement stresses up to 60 MPa and axial stresses up to 270 MPa can be applied. Several steps of deviatoric compression were performed during which permeability measurements were done. Three measurements have been made, corresponding to 10 kN load (20% of the failure stress), 45 kN (90% of the failure stress) and after failure. Results show that, the more loaded the sample, the larger the slope of the input pressure versus time curves. This means that the time back to pressure equilibrium in the "reservoir + specimen" system decreases, which is the indication of an increase in permeability.

In addition, the first results of the permeability measurements on the deep argillaceous rock from the French site will be presented.
TUNNEL MODEL TEST OF ARTIFICIAL SOFT ROCK AND PROPOSAL OF TUNNEL SUPPORT DESIGN

Takeo Kaneko, Hideyuki Horii, Toshihiro Koyama

1. Tokyo Electric Power Services Co., Ltd., 3-3-3 Higashiueno, Taito-ku, Tokyo 110-0015, Japan
2. University of Tokyo
3. Tokyo Electric Power Services Co., Ltd

Disposal facility of radioactive waste is planned to construct in deep underground. Up to now there have been few experiences of construction in such a deep underground. Therefore, tunnel design cannot rely on the experiences and should be based on real phenomena, the real phenomena of the tunnel failure, however, have not been clarified yet. As a tunnel failure, the following process is supposed; at first stress release during excavation causes stress concentration in tunnel wall, and rock mass around the tunnel surface reaches failure state and progress of the failure plane makes tunnel unstable.

In this study, tunnel model tests are conducted in order to investigate the real phenomena of tunnel by using artificial soft rock specimens. Then we propose a new design concept of tunnel support design.

Artificial soft rock consists of Toyoura sand (69.6%), gypsum (11.6%) and water (18.8%). The size of specimen is 40(Wide) * 25(Height) * 10(Depth) cm and tunnel (diameter 5cm) is set to almost center of the specimen (see Fig.1). A steel frame constrains the Depth direction perfectly and load is applied to the specimen under plane strain condition. Constant pressure (0.15Mpa) is applied to the edge in the Wide direction by using flat jack and displacement rate on the edge in the Height direction is controlled at a rate on 3mm per minute by servo actuator. From front window of the steel frame, behavior of rock mass is observed and measured by a highly accurate measurement system, which adopts an image analysis by using XY stage, microscope and CCD camera.

As shown in Fig. 2, progress of failure around the tunnel is observed in this experiment. At 5th step there is no localization of deformation, however at 8th step localization starts from side wall surface and expand widely in proportion to increasing of loading. Finally, wedge shape rock mass fall into inside of tunnel (see Fig.3). Consequently, a formation of wedge shape rock mass is regarded as a collapse of tunnel, which is a limit state.

For considering discontinuum plane that forms wedge shape rock mass, FEM analysis that contains discontinuum planes is performed. In this study, the discontinuum plane is modeled by interface element that can express behaviors of discontinuum plane. Material property of the interface element is supposed to be residual state, therefore the cohesion is reduced to 1/4 of initial strength.

In this research, two limitation of depth are proposed as a design concept of tunnel support. First limitation is that there is no element that reaches failure criteria. The other one is a state that all discontinuum elements reach to failure criteria and wedge shape rock mass fall into inside of the tunnel, which means instability. According to this concept, we estimate the limitation depth of tunnel construction. Analytical results indicate that the analysis with discontinuum plane elements can design tunnel in deeper underground.
Figure 1

Figure 2

Figure 3
POROPLASTIC DAMAGE MODEL FOR 
GEOMATERIAL

Nathalie CONIL-AUBLIVÉ1,2, Irini DJERAN-MAIGRE1, Richard CABRILLAC1, 
Kun SU2

1. Laboratoire Matériaux et Sciences des Constructions, 5 mail Gay Lussac, Neuville 
sur Oise 95031 Cergy-Pontoise Cedex
2. Agence nationale pour la gestion des déchets radioactifs, Parc de la Croix Blanche, 
1-7 rue Jean Monnet, 92298 Châtenay-Malabry Cedex

We present in the paper a poroplastic model to describe the behaviour of deep argillaceous 
rocks, we chose to develop a model with anisotropic damage as part of the saturated porous 
media mechanics associated with damage mechanics.

Firstly a poroelastic anisotropic damage model is used to describe the degradation of the rock. 
The damage variable is a 2nd order tensor, which makes it possible to take into account the 
induced microfracture anisotropy.

The equation of the problem are:

\[
\varepsilon_{ij}^f = \varepsilon_{ij}^f + \varepsilon_{ij}^p
\]

\[
\varepsilon_{ij}^f = \frac{1+v}{E} \sigma_{ij} - \frac{v}{E} \sigma_{kk} \delta_{ij}
\]

\[
\sigma_{ij} = \left(H_{\delta_{ij}} \sigma_{ij}^D H_{\delta_{ij}}\right)^{0.5} + \frac{\sigma_H}{1-d_H} \delta_{ij}
\]

\[
H_{\delta_{ij}} = \left(\delta_{ij} - D_{\delta_{ij}}\right)^{1/2}; d_H = \eta D_H = \frac{\eta}{3} D_{kk}
\]

It is supposed therefore that the damage appears when an equivalent strain reaches a threshold 
which depends on the state of current damage. The proposed damage criterion (Chiarelli, 
2000) is written:

\[
f^d(\varepsilon, D) = \varepsilon - \sigma - \sigma\text{tr}D
\]

The chosen approach (Aublivé et al., 2001) shows the characteristic to consider the 
anisotropic character of the matrix behaviour induced by the damage and to reproduce the 
anisotropic evolution of the tensor of hydromechanical coupling (tensor of Biot coefficients) 
according to degradations of the skeleton (Bart, 2000):

\[
B(D) = B^0 + C_{ij} D + C_{ij} \text{tr}D
\]

The second order tensor \(B^0\), defines Biot's coefficients of non damaged material and \(B\) is a 
second order tensor representing the hydromechanical coupling.

This model is coupled with a plastic model. Then, in keeping with the experimental 
observations, the plastic yield function suggested is based on the Drücker-Prager criterion. 
While supposing moreover one isotropic work hardening and a perfectly plastic response in 
hydrostatic tensile, the plastic yield function is written:

\[
f \left(\sigma, V_h\right) = \tau h(\theta) + f(\sigma + \beta p - \rho) \leq 0
\]

\(p\) is the pore pressure and \(\beta\) is a constant depending on material. The Lode angle \(\theta\) is 
introduced so as to have a different plasticity threshold in compression and extension. \(\tau\) is the
generalized deviatoric stress expressed, the parameter $\rho$ represents the hydrostatic tensile strength of material, which is taken constant here. $f$ represents the isotropic plastic hardening, depending on $\gamma^p$ the equivalent plastic shear strain.

As for most rock materials, plastic flow is generally non-associated. Thus, one shows that the porous mechanics constitutes a powerful framework for the study of the fluid-solid interactions in porous materials. The reproduction of the poroplastic behaviour is based on a criterion which takes into account the followed stress path, an isotropic hardening and a non-associated law. The influence of the damage on plasticity is introduced by means of the effective stress tensor.

References


In order to guarantee safety of deep geological underground waste disposal, it is necessary to control hydraulic properties of the ground. If we want to predict the extension of the damage zone produced by excavation of galleries we have to make use of a damage model suitable for hydro-mechanical coupling. EDF/CIH established such a rheological law for argilites and weak rocks. The physical phenomena taken into account are the initial cohesion, the maximum value for the shear stress (beyond this point, shear resistance decreases as much quickly as confinement is low), the evolution of dilatancy angle, and an ultimate state with no cohesion, some friction angle and null dilatancy. The mathematical formulation of the law is based on non associated plasticity. The elastic domain is defined by equation:

\[
f(\sigma, \gamma^p) = \left( \frac{s\mu h(\theta)}{\sqrt{6} \sigma_c} \right) \gamma^p + m(\gamma^p) \left( \frac{h(\theta)}{h^0} \right) + \frac{m(\gamma^p)}{3 \sigma_c} I_1 - s(\gamma^p) \leq 0
\]

Where \( s = \sigma - \frac{Tr(\sigma)}{3} \), \( s_{\mu} = \sqrt{s} s \), \( I_1 = Tr(\sigma) \), \( h(\theta) = (1 + \gamma_{cjs} \cos(3\theta))^{1/6} \) and \( \theta \) is the Lode angle. \( \sigma_c, h^0 \), \( \gamma_{cjs} \) are constant coefficients depending on the material and \( a(\gamma^p), m(\gamma^p), k(\gamma^p), s(\gamma^p), k(\gamma^p) \) are functions of the equivalent plastic shear deformation used as the unique softening variable \( \gamma^p \): \( d\gamma^p = \frac{2}{3} \text{dev}(de\gamma^p) \).

The elastic domain is a generalization of Hoek and Brown criterion, using a variable exponent instead of fixed square value used in classical Hoek and Brown formulation. When drawn in the deviatoric plane, the yield surface is close to the Ladde criterion. Evolution of plastic deformations is given by equation:

\[
\dot{\varepsilon}^p = \dot{\lambda} \left( \frac{\partial f}{\partial \sigma} - \frac{\partial f}{\partial \sigma} \right) n
\]

where unit vector \( n \) depends on dilatancy angle \( \psi \) and ensures the following relationship between the plastic volume change \( \varepsilon^p \) and the plastic strain energy change \( s.\dot{\varepsilon}^p = \frac{2\sqrt{6} \sin \psi}{3 - \sin \psi} \cdot \frac{s.\dot{\varepsilon}^p}{s_{\mu}} \).

The rheological law described below is introduced in the general non linear Newton algorithm for solving equilibrium equations of Code_Aster. It needs to solve for each global Newton iteration and for each gauss integration point a local non linear problem in order to find stresses and internal variables corresponding to a given deformation tensor. At this stage, we choose an implicit formulation with respect of stress criterion and an explicit one with respect of plastic flow direction. When denoting with subscript – and + the quantities at the beginning and the end of the time, the set of local non linear equations is:

\[
\sigma^+ = \sigma^- - \nabla \left( \varepsilon^{p+} - \varepsilon^{p-} \right) ;
\varepsilon^{p+} - \varepsilon^{p-} = \left( \lambda^+ - \lambda^- \right) \left( \frac{\partial f}{\partial \sigma} - \frac{\partial f}{\partial \sigma} \right) \n
\]

\[
(3)
\]
\begin{equation}
\begin{aligned}
f\left(\sigma^+,\gamma^{p+}\right) &\leq 0 \quad ; \quad \left(\lambda^+ - \lambda^-\right)f\left(\sigma^+,\gamma^{p+}\right) = 0
\end{aligned}
\end{equation}

The intersection of plastic surface with hydrostatic axes is a singular point where \( \frac{\partial f^-}{\partial \sigma} \) is not defined. The solution \( \left(t^+_1, s^+_1\right) \) is the oblique projection on the criterion of elastic point \( \left(t^e_1, s^e_1\right) \). Then we can estimate two values of the projection angle, which determine two zones. If \( \left(t^e_1, s^e_1\right) \) belongs to the first one, equations (3) to (4) have an unique solution corresponding to a regular projection, if \( \left(t^e_1, s^e_1\right) \) belongs to the second one, there is no regular solution and final point is the top of elastic domain (intersection with hydrostatic axes). In the intermediate zone, we tend to solve equations (3) to (4) and, when no convergence occurs, we select top point as solution. This gives accurate solutions for a triaxial test with argilite material characteristics:

\begin{align*}
\text{Shear stress/ axial deformation} & \quad \text{Volume change / axial deformation}
\end{align*}
AN INDIRECT APPROACH TO PREDICT BIOT'S COEFFICIENT OF ARGILLACEOUS ROCKS

Ph. Cosenza 1, M. Ghoreychi 2, G. Vasseur 1, S. Violette 1

1. UMR 7619 Sisyphe, Paris VI University, 4 place Jussieu, 75252 Paris Cedex 05, France
2. Institut National de l'Environnement Industriel et des Risques (INERIS), Verneuil-en-Halatte, France

The coupling of stress-strain and pore fluid pressure in deep clayey rocks is of interest to many academic and practical problems in Earth Sciences: pore pressure build-up resulting from compaction of sedimentary basin during its formation; the hydromechanical behaviour of clayey rocks due to excavation of drifts or deep repositories and the hydromechanical response of disposal of nuclear waste due to heating. All these problems involve strong coupling between pressurization, motion of fluid and deformation of the porous rock. The theoretical pioneering work on hydromechanical behaviour of isothermal porous media was that of Biot (1941). Rice and Cleary (1976) have developed general solutions to classical initial/boundary value problems and recast Biot’s theory in terms of new material parameters, more directly open to physical interpretation.

These poroelastic parameters are measured by using “drained” and “undrained” triaxial compression tests. The terms “drained" and “undrained" refer to boundary conditions in which there are no changes in pore fluid pressure and pore fluid mass, respectively. However, considering tight argillaceous rocks, it is not practical to measure all the poroelastic parameters, in particular the “drained” elastic moduli. Indeed, considering low permeability media with conductivities between $10^{-12}$ and $10^{-14}$ m/s, it is difficult to measure and a fortiori to control pore pressure in the sample. These measurements require special experimental techniques with a severely controlled tightness and may lead to unacceptably long durations.

Consequently, it is desirable to have some methods of correlating the “drained” elastic moduli to physical parameters, which would be easier to obtain experimentally. One idea, which has been used initially by Green and Wang (1990), is to relate the “drained” bulk modulus to the specific storage coefficient that is usually measured in hydraulic field tests. This relationship is investigated in order to answer to the following question: how can one use the in situ argillaceous rocks specific storage measurements to calculate their poroelastic properties?

The proposed method is shown to provide simply and rapidly an estimation of the poroelastic properties of isotropic argillaceous rocks from parameters taken from different scientific fields (petrophysics, geomechanics and hydrogeology) (Figure 1). In particular, this method is based on an equation similar to that of Green and Wang, which is reformulated in order to introduce the “undrained” bulk modulus, more practical to measure in argillaceous rocks. This approach requires a value of the specific storage coefficient obtained from “modified” slug tests or "pulse" tests for low-permeability formations. The assumptions and underlying uncertainties of such an approach are discussed and an attempt to validate it, is proposed. This approach is applied to three deep argillaceous formations from the Paris sedimentary basin (taken at a 693 m to 866 m depth). The results show a satisfactory agreement with direct measurements from special hydromechanical tests performed on the Callovo-Oxfordien formation.
Moreover, an expression is established by linking the specific storage coefficient to poroelastic constants from *transversely* isotropic clayey rocks. In this particular condition of anisotropy, a set of non-linear equations is derived and solved numerically to obtain the main poroelastic properties of the Domerien-Toarcien shale from the Tournemire site in Southern France. In both cases (isotropic and anisotropic), calculations show that these methods are very sensitive to the values of the specific storage coefficient, which have to be measured with accuracy.

![Diagram of the integrated approach](image)

**Figure 1.** Diagram of the integrated approach

**References**


POROELASTIC PARAMETERS OF MEUSE / HAUTE - MARNE ARGILITES : EFFECT OF LOADING AND SATURATION STATES

E. Bemer, P. Longuemare, O. Vincke

Institut Français du Pétrole (IFP), Rueil-Malmaison, France

This paper will present a synthesis of the experimental work conducted by IFP on rock samples taken out of the Meuse/Haute Marne underground research laboratory host formation, named “argilite”. The behavior of this clayey rock has been studied within the framework of Biot’s mechanics of fluid saturated porous solids. Drained and undrained uniaxial strain tests (“oedometric tests”, Fig. 1) have been performed to determine the poroelastic parameters for various applied stresses: drained and undrained bulk moduli $K_o$ and $K$, shear modulus $G$, Biot coefficient $b$ and Biot modulus $M$.

The theoretical relations used to determine the hydromechanical parameters suppose that the rock is saturated. As the provided plugs were not saturated, a particular care has been given to the definition of a preliminary resaturation phase of the samples and the estimation of their final saturation.

The obtained results show an influence of the applied stress on the poroelastic parameters: the measured Biot coefficient decreases when the axial stress increases, while the drained bulk modulus and the shear modulus increase (Fig.2). The effect of the applied stress on the Biot modulus is more difficult to interpret, because its measure strongly depends on the saturation state of the sample.

The argilites poromechanical behavior appears to depend on the rock saturation state: samples with a greater initial saturation seem to show a lesser apparent surconsolidation degree and a higher compressibility.

The full paper will describe the followed experimental method, including the resaturation phase, the loading path and the estimation of the sample saturation. The experimental results will be analyzed to show the influence of both the saturation state and the applied stress.
Figure 1: Oedometric curve of an argilite sample

Figure 2: $K_o + 4G/3$ as a function of the applied axial stress
HYDROMECHANICAL TESTING OF AN ARGILLACEOUS ROCK.
EXPERIMENTAL SET UP AND TESTING PROCEDURE

L. Malinsky ¹, S. Chanchole ¹, F. Coste ²

1. G.3S, Ecole polytechnique
2. EEGL Simecsol

Argillite of Haute-Meuse (East of France) is a potential host rock for a radioactive waste repository. An underground research laboratory (URL) is currently under construction. Before completion of the URL laboratory, testing is performed in order to understand the thermohydromechanical behavior of this argillite, to predict the consequences of shaft and galleries excavation and to design in situ experiments. However, many difficulties arise when testing such a rock at laboratory scale. The very low permeability of the Haute-Meuse Argillite (in the range of $K=10^{-21} \text{ m}^2$ for the intact rock) requires a specific experimental device to allow accurate measurements of HM properties over long periods of time. A major difficulty is to bring the tested sample at the in situ stress, water content and pore pressure conditions prior to testing. In order to minimize chemical interactions the injected fluid is a mixture of water and argillite powder. The pulse test method has been selected to determine both the permeability and the storage coefficient of the rock under the assumption of a poroelastic behavior. Analysis of drained isotropic consolidation path allows to check the reliability of the set of parameters derived from the pulse test (Coste & al. 1999).

The device is designed to compensate thermal fluctuations which generate undesirable apparent pore pressure variations. A reference circuit, whose compressibility is the same as the compressibility of the reservoir used to perform the pulse test, is heated in order to keep circuit pressure constant. The same amount of heat is provided to the reservoir in order to compensate thermal fluctuations up to $5^\circ\text{C}$.

In this paper, we report the results obtained from two samples submitted to hydromechanical loading during four and five months respectively. The results show some characteristic features of a poroelastic behavior but also exhibit a long term swelling, which is not restricted to the early testing times when the sample is under resaturation prior to hydromechanical loading. Figure 1 exhibits a quasi-linear swelling behavior under constant loading that was observed during 40 days. This behavior has already been observed by other authors (Vales & al. 2001). Figure 2 shows the results of a pulse test. The asymptotic pressure is lower than the initial pressure, which is not in agreement with a poroelastic behavior. The very low drained bulk moduli derived from isotropic consolidation path analysis indicate sample fracturing which was observed after the end of the tests for the two samples although an isotropic loading had been applied during the tests.

References

Figure 1: A quasi-linear swelling of $6.6 \times 10^{-5} \text{s}^{-1}$ under constant loading is observed during 40 days. Poroelastic isotropic consolidation takes place from day 40 to day 68.

Figure 2: Results of a pulse test on sample n°2. From day 48 to 51, pore pressure is kept at a constant value of 1 MPa at the two ends of the sample. Some water is absorbed by the sample at a linear rate. At the day 51, a 1 MPa pressure jump is applied during a short period of time and the sample is insulated. The decrease of the pressure at the two ends under the 1MPa initial value cannot be explained by a poroelastic model.
THE MONT TERRI UNDERGROUND ROCK LABORATORY : GEOMECHANICAL ANALYSIS

P. Blümling 1, H.J. Alheid 2, C. Bauer 3, J.Y. Boisson 4, S. Yamamoto 5

1. Nagra, Switzerland
2. BGR, Germany
3. Andra, France
4. IRSN, France
5. Obayashi, Japan

Introduction
The Mont Terri Underground Rock Laboratory is situated in the Swiss Jura mountains in the République et Canton du Jura. Using the existing highway tunnel system as access to the Opalinus Clay, a number of niches were constructed along the reconnaissance gallery to explore the possibilities to use this area as a research facility. In 1998, it was decided to construct a new laboratory tunnel with various annex rooms to continue and intensify the research work. Today, 10 institutions from 6 different countries participate in the Mont Terri Project which is directed by the Swiss Federal Office for Water and Geology.

A key emphasis of the experiments at Mont Terri is the investigation of the geomechanical behaviour of the Opalinus Clay which is a claystone with a significant anisotropy in its physical parameters due to the bedding. It is clear that the description of such a material with relatively high porosity (12-15%) and low hydraulic conductivity (5 x 10^{-13} m/s) would be incomplete without the consideration of coupled processes. Basis for the geomechanical synthesis are several in-situ tests (e.g. mine-by-test) as well as a large number of laboratory tests.

The objectives of the geomechanical investigations are to deliver information for the construction and operation of tunnels in a claystone and to increase the knowledge on the long-term performance of such a rock under repository conditions. Therefore, it was decided to proceed the following way:
- establish a conceptual rock mechanical model,
- verify the conceptual model using a micro-mechanical modelling approach (PFC),
- establish and verify a constitutive model.

Conceptual Model and Micro-mechanical Modelling
The conceptual model, developed for the Opalinus Clay, is based on the assumption that the deformation of such a clay is mainly controlled by its internal structure and the interaction of the clay particles, the bound and the free water. The basis of the theory is that molecules and/or particles, termed “flow units”, are participating in and, in fact, controlling time-dependent deformation processes.

The elastic behaviour is mainly governed by the deformation of the skeleton of clay particles and the relevant deformation mechanism will be deflection of these particles. The consolidation behaviour is governed by the squeezing of free water in the pores while the creep behaviour can be characterised as delayed, permanent and non-reversible deformations, due to breakage of the bonds between particles (cataclastic flow). Material strength mainly depends on load direction with respect to the bedding planes, water content and confining pressure. Of minor importance are load rate, temperature and the mineralogical composition.
Micro-mechanical Particle-Flow-Code (PFC) modelling was performed in addition to classical continuum-mechanical calculation to get an understanding of the material behaviour on the microscopic level. The model, consisting of several thousand clay particles, was created starting from a random distribution of particles and a simulation of the compaction history. This model was then used to investigate the deformation behaviour of the clay. Although relatively simple interaction between the different particles was used (linear shear and normal stiffness, shear and tensile strength), it was possible to model observed phenomena like strain-hardening in the pre-failure domain, strain softening in the post failure domain as well as cataclastic creep and a hysteresis behaviour during a loading / unloading cycle.

Constitutive Law
Based on a constitutive law developed within Nagra's feasibility study on Opalinus Clay as a potential host rock for a repository for radioactive waste, a law for the Opalinus Clay at Mont Terri was developed. In general, a bi-linear Mohr-Coulomb law with an ubiquitous joint model was used that accounts for the anisotropic strength of the rock. The hydro-mechanical coupling was introduced through a coupling with a routine to calculate a Darcy flow (anisotropic hydraulic conductivity). The time dependent deformation was controlled through the hydro-mechanical coupling and the Salzer creep law which was originally developed for salt creep and calibrated with laboratory creep data from Mont Terri.

The numerical calculations were compared with a in-situ mine-by experiment at Mont Terri. The model results are able to predict the instantaneous undrained deformation as well as the observed failure mechanisms. In contrast, the time dependent deformations were largely overestimated by the initial model, based on the laboratory results. The introduction of a threshold value for the onset of the creep (similar to a Bingham rheological model) which is compatible with the conceptual model allowed to explain both - the laboratory and in-situ data.
STUDY OF THE CREEP BEHAVIOR OF BURE CLAYEY ROCK

M. Gasc-Barbier 1, S. Chanchole 1, B. Lecampion 1, P. Bérest 1, N. Hoteit 2

1. G.3S, Ecole polytechnique, 91128 Palaiseau cedex
2. Andra

In order to characterize the delayed behavior of Bure host rock, a comprehensive creep testing program was defined by G.3S, Ecole Polytechnique, in close cooperation with ANDRA. This program includes: four one-year-long tests under constant deviatoric stress; six four-month-long tests including three one-month-long steps, each of them being characterized by a different deviatoric stress level; four creep tests performed at a 80°C temperature; and four tests performed on “damaged” samples to investigate the behavior of the rock at the gallery wall. During each of these eight last tests, samples were submitted to the same stress level as during the ambient multi-step creep tests, in order to allow direct comparison of their mechanical properties. Figure 1 shows the strain-versus-time curve obtained for all the undamaged samples submitted to creep tests; Table 1 gives the testing conditions.

Testing conditions are of prior importance in this kind of long term experimental program. Special attention was kept on the initial state of the samples. In the current study, we submitted all the tested samples to a nearly one-month-long resaturation period. In order to prevent chemo-mechanical coupling, we chose to use especially prepared water. A small part of the sample was crushed to powder, which was then mixed with distilled water. Special attention was given to prevent particle oxidation. Before application of deviatoric (or temperature) loading, the prepared water was injected in the sample at a pressure of 5 MPa during one month, and deformations were measured.

The main results of this testing program are summarized here:
- even after 18 months of constant loading, deformations did not stabilize, and the deformation rate seems to be constant;
- the so-called “resaturation step” is of great importance: deformations obtained during this step are larger than the ones obtained after one month under 10 MPa deviatoric stress, but we are still not able to say if they are due to real resaturation, to swelling or to chemical transformation;
- comparison between observed strain and strain rate shows the importance of the loading history. For example strain and strain rate are smaller under a first step at 10 MPa of deviatoric stress than if it is reached after two steps (at 2 and 5 MPa loading);
- creep exists even under 2 MPa deviatoric stress, which enable us to consider that there is no stress threshold for the onset of creep.
Figure 1: Strains on all the tested samples

Table 1: Testing conditions

<table>
<thead>
<tr>
<th>N°. EST</th>
<th>under layer</th>
<th>N° samp</th>
<th>depth M</th>
<th>T (°C)</th>
<th>Resaturation</th>
<th>1st step * Q-P / time [j]</th>
<th>2nd step * Q-P / time [j]</th>
<th>3rd step * Q-P / time [j]</th>
<th>commentaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>5697 C1 2</td>
<td>491,6</td>
<td>amb</td>
<td>22</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Still in load</td>
</tr>
<tr>
<td>5697 C1 7</td>
<td>491,8</td>
<td>amb</td>
<td>28</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5721 C2 1</td>
<td>497,6</td>
<td>amb</td>
<td>22</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Still in load</td>
</tr>
<tr>
<td>5721 C2 2</td>
<td>497,6</td>
<td>amb</td>
<td>31</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Still in load</td>
</tr>
</tbody>
</table>

Long term creep test

<table>
<thead>
<tr>
<th>N°. EST</th>
<th>under layer</th>
<th>N° samp</th>
<th>depth M</th>
<th>T (°C)</th>
<th>Resaturation</th>
<th>1st step * Q-P / time [j]</th>
<th>2nd step * Q-P / time [j]</th>
<th>3rd step * Q-P / time [j]</th>
<th>commentaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>5697 C1 4</td>
<td>491,7</td>
<td>80</td>
<td>21</td>
<td>10 / 33</td>
<td>15 / 38</td>
<td>20 / 1</td>
<td>Rupture at 20 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5697 C1 5</td>
<td>491,7</td>
<td>amb</td>
<td>22</td>
<td>10 / 31</td>
<td>15 / 30</td>
<td>10 / 33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5697 C1 6</td>
<td>491,7</td>
<td>amb</td>
<td>22</td>
<td>2 / 31</td>
<td>5 / 30</td>
<td>10 / 34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5698 C1 1</td>
<td>491,9</td>
<td>80</td>
<td>30</td>
<td>2 / 30</td>
<td>5 / 30</td>
<td>10 / 32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5698 C1 3</td>
<td>491,9</td>
<td>amb</td>
<td>27</td>
<td>10 / 32</td>
<td>15 / 56</td>
<td>17 / 34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5698 C1 4</td>
<td>492,4</td>
<td>amb</td>
<td>100</td>
<td>2 / 70</td>
<td>5 / 35</td>
<td>10 / 35</td>
<td></td>
<td>Damaged sample</td>
<td></td>
</tr>
<tr>
<td>5698 C1 5</td>
<td>492,4</td>
<td>amb</td>
<td>70</td>
<td>10 / 70</td>
<td>15 / 35</td>
<td>18 / 35</td>
<td></td>
<td>Damaged sample</td>
<td></td>
</tr>
<tr>
<td>5721 C2 3</td>
<td>497,6</td>
<td>amb</td>
<td>28</td>
<td>10 / 30</td>
<td>15 / 33</td>
<td>10 / 34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5721 C2 5</td>
<td>497,7</td>
<td>80</td>
<td>25</td>
<td>10 / 30</td>
<td>15 / 40</td>
<td>18 / 30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5721 C2 7</td>
<td>497,7</td>
<td>amb</td>
<td>26</td>
<td>10 / 30</td>
<td>15 / 39</td>
<td>18 / 187</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5721 C2 9</td>
<td>497,9</td>
<td>amb</td>
<td>21</td>
<td>2 / 31</td>
<td>5 / 36</td>
<td>10 / 157</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5721 C2 11</td>
<td>497,9</td>
<td>80</td>
<td>50</td>
<td>2 / 30</td>
<td>5 / 32</td>
<td>10 / 80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5721 C2 11</td>
<td>497,9</td>
<td>amb</td>
<td>33</td>
<td>10 / 102</td>
<td>15 / 35</td>
<td>18 / 35</td>
<td></td>
<td>Damaged sample</td>
<td></td>
</tr>
<tr>
<td>5722 C2 2</td>
<td>498</td>
<td>amb</td>
<td>50</td>
<td>2 / 70</td>
<td>5 / 35</td>
<td>10 / 35</td>
<td></td>
<td>Damaged sample</td>
<td></td>
</tr>
</tbody>
</table>
INTERACTION BETWEEN CREEP, SWELLING AND PRESSURE - SOLUTION DURING INDENTATION TESTS

F. Valès, P. Bérest, H. Gharbi

LMS, Ecole polytechnique, Palaiseau

This study was performed under FORPRO Research Contract OO-I, in cooperation with J.P. Gratier LGIT, Grenoble.

The mechanisms governing argillite mechanical behavior are still incompletely known. Previous tests on Bure argillite have proven that this rock, when submitted to large deviatoric stresses (say, 10 MPa) exhibit strain rates of the order of $3 \times 10^{-11}$ s$^{-1}$ to $3 \times 10^{-10}$ s$^{-1}$, rates which are significant enough when one considers deep underground galleries which will remain opened during one century.

Extrapolation of few-month-long creep tests to much longer period of times must be based on a better understanding of the mechanisms governing argillite behavior. As Bure argillite contains a relatively high amount of carbonates, effects of pressure-solution mechanisms were suspected to be of some importance. Standard indentation tests, involving high applied forces, are performed in LGIT, Grenoble. This effort is completed by similar tests performed under small mechanical loading by LMS, Palaiseau; these tests are described in this paper.

Five indentation tests have been performed. During each test, three indents, 5.2 mm in diameter, are pressed on an argillite sample; the loading stress is in the order of 3 MPa. Under such a load, very slow penetration rates are expected. For this reason high resolution strain measurement sensors are used and the room temperature and hygrometry are made quite stable by setting the testing apparatus in a gallery of an old underground quarry, 20 m below ground level.

A testing fluid is placed above the sample surface. Various testing fluids were used to assess their effect on indent penetration rate. The obtained results are somewhat surprising. For instance, when ethanol is used as a testing fluid, penetration rate is negative: in other words, sample swelling is much faster than sample creep below the rigid indent. This result can be compared to similar observations performed during standard creep tests: when low compressive stresses are considered, sample swelling is significantly larger than sample creep. However when no fluid is used, a stabilized penetration rate ($3 \times 10^{-12}$ m.s$^{-1}$ is a typical figure) can be observed after a couple of weeks. When pure soft water is used as a testing fluid, penetration rate are very large and it is observed at the end of the test that cylindrical holes have formed on the surface sample.

This set of results proves the significance of the chemical composition of the testing fluid when mechanical behavior is considered, with potential consequences for the prediction of the long-term evolution of underground galleries.
CHARACTERISATION OF COMPLEX MEDIA: BACKSCATTERING FROM ROUGH INTERFACES

Stéphanie Gautier, Dominique Gibert

Géosciences Rennes UMR 6118 & GdR FORPRO, Laboratoire de Géophysique Interne, Campus de Beaulieu, 35042 Rennes Cedex, France

Geophysical imaging of complex media is often faced with rough interfaces (faults and fractures, the sea surface and the seafloor, geologic discontinuities, etc). The roughness of discontinuities have an important place in numerous phenomena such as fluids flow through fractures, the frictional behaviour of faults, the chemical and physical exchanges at an interface, etc. The roughness also gives us information about the structure and the nature of the interface. It is important to estimate this parameter to describe correctly the discontinuity. The aim of this study is to perform a method to characterise the roughness of an interface from backscattering measurements.

In the case of small roughness and in the single scattering approximation, the observed amplitude of the backscattered wavefield can be interpreted as the Fourier transform of the roughness which in turn may be described in terms of fractal properties of the surface. The measurement of the backscattered wavefield leads consequently to a characterisation of the surface in terms of fractal dimensions. The principal theoretical result is a power-law linking a certain average of the scattering intensity of the horizontal component of the transfer momentum across the interface. The fractal wavelet correlation dimension is the exponent which quantifies the roughness of the surface: the smaller the exponent, the rougher the interface. It is an extension of the standard correlation dimension. We propose a method to extract the fractal wavelet correlation dimension from an acoustic backscattering experiment.

We study the acoustic wavefield backscattered by a granite surface to characterise the roughness of the discontinuity in an acoustic small scale experiment. We emit wavelets at different frequencies and under varying acquisition geometries (different incident and reception angles of the transducers). The family of wavelets are sent on a resin copy of a granite surface (separation of influence of mineralogy). This leads to an experimental wavelet analysis of the roughness of the surface.

We present a procedure based on the generalised wavelet inversion formula which allows the construction of the experimental filter to deconvolve data from distortions due to instrumental devices.

We apply the same method to backscattering data to build the transfer filters of the interface. A stacking method based on the small amplitude approximation allows the estimation of the orientation of the local incidence plane which could not be measured directly. The fractal wavelet correlation dimension is then estimated by studying a power-law associated with the adjusted data.
We also perform numerical experiments to validate the stacking procedure and the estimation of fractal dimension. The rough interface is modelled by multi-scale planar and quasi-planar distributions of diffracting points. We generate synthetic backscattering data from such interfaces that allows for the shape and the aperture of the transducers as well as the finite distance between transducers and the surface.

We also study the acoustic wavefield backscattered by resin copies of a granite sample which has been eroded. For each sample, a family of wavelets is emitted at different frequencies and we record the angular variation of acoustic intensity for a fixed incident angle. We analyse if measurements of angular variations of backscattered intensity allow the interfaces of the various samples to be distinguished and to give us information on the degree of erosion of each one.

References
Gautier S., Holschneider M., Estimation of the orientation of the local incident plane from backscattering experiments, in prep.
SEISMIC ENDOSCOOPY : EXPERIMENTS AND 3D IMAGING

Florence Nicollin, Frédéric Conil, Dominique Gibert

Géosciences Rennes UMR 6118 & GdR FORPRO, Laboratoire de Géophysique Interne, Campus de Beaulieu, 35042 Rennes Cedex, France

Seismic endoscopy is an acoustical method to perform high resolution 3D imaging around shallow depth boreholes. Embedded in an absorbing material, piezoelectric transducers work in the 30-100 kHz frequency range as directional receivers, recording waves transmitted by an isotropic source and propagating in the surrounding medium. The probe geometry offers data depending on time, transmitter depth, source-receiver distance (called offset as in surface seismic), and earring azimuth. By extraction of the reflected waves from the recorded fullwaveform, the discontinuities are imaged in a cylindrical volume a few meters in radius, with a centimetric accuracy and an azimuthal directivity of 25 degrees.

Several prototypes of endoscopic probe have been designed and validated by experiments in an acoustic tank and in a test site. Specific processing algorithms have been developed, using the four dimensional dependence of the signal (time, depth, offset and azimuth), to enhance reflected echoes from the medium inhomogeneities.
CHARACTERISATION OF COMPLEX MEDIA: MULTIPLE SCATTERING OF ELASTIC WAVES

Yves Le Gonidec, Dominique Gibert

Géosciences Rennes UMR 6118 & GdR FORPRO, Laboratoire de Géophysique Interne, Campus de Beaulieu, 35042 Rennes Cedex, France

To characterise complex media, we have developed a multiscale method using the acoustic waves reflected at the interface.

1. The wavelet response
We show that, in the case of an homogeneous discontinuity present in a velocity profile (Dirac and Heaviside discontinuities for instance), we obtain the regularity of the discontinuity by its wavelet transform that has a cone-like structure pointing towards the spatial position of the abrupt change. For a multiscale discontinuity, such as a windowed function (two consecutive Heaviside distributions), we observe a hierarchical arrangement of conical patterns and the changes are equivalent to locally homogeneous discontinuities following the frequency range. For such an analysis, the velocity profile has to be known and we generalise this approach by replacing the correlating operator by directly propagating the wavelets into the medium. Equivalent to the wavelet transform under the Born approximation, this wavelet response is numerically obtained by 1-D finite difference modellings that are in accordance to the wavelet transforms of synthesis cases [2].

2. Experimental validation of the method
Through a non-linear inverse method [1], we search for the input numerical signals to be emitted in transmission to measure the imposed wavelet family: this is our wavelet response reference. Experimentally, we apply the wavelet response method with reflectors immersed in a water tank. A polycarbonate plate models the case of a windowed discontinuity where the wavelet family is reflected. This constitutes the wavelet response that covers 5 dilation octaves (150kHz-1.2MHz). As predicted by the modelling, we note a critical frequency indicating twice the thickness of the plate [3]. It is due to interference phenomena inside the target. Below this value, the reflector appears as a Dirac discontinuity when at higher frequency, it has an Heaviside-like appearance since its internal structure is detected. We characterise the multiscale reflector by its wavelet transform that is then validated experimentally.
3. Granular medium characterisation

We characterise an heterogeneous medium made of glass beads by the use of the wavelet transform (100kHz-5MHz). Five dilation ranges are identified [4]. For the long wavelengths, the complex interface is equivalent to an Heaviside discontinuity. When the wavelength of the incident wavelet is around the bead diameter, multiple scattering is dominant and the lateral diffusion locally reduces the reflection coefficient. The effective medium model of Waterman and Truell is in good agreement with the data and its validity limit occurs when the frequency is so high that only the surface of the glass bead medium reflects the waves.

References

MACROSCOPIC MECHANICAL PROPERTIES OF
FRACUTURED CLAYS

I.I. Bogdanov 1,2, V.V. Mourzenko 2, J.F. Thovert 2, P.M. Adler 1

1. IPGP, tour 24, 4 place Jussieu, 75252 Paris Cedex 05
2. PTM/LCD, BP179, 86962 Futuroscope Cedex

1. Introduction
The major purpose of this starting research is the description of the mechanical reaction to tunneling. Two major phases can be a priori distinguished; the first one corresponds to the fracturation of the clay, just after drilling, the second to the creep of the fractured material which may be followed by a possible progressive closing of the fractures. These structural variations are likely to induce modifications to the hydraulic and transport properties of the damaged zone.

This first step is focused on the implementation of a general methodology to address these questions. This general methodology is described in Section 2 and some preliminary tests are presented and discussed in Section 3.

2. General methodology
This topic belongs to the general field of fractured porous media (Adler and Thovert, 1999). An example of such a medium is displayed in Fig.1a. The precise study of such media necessitates their discretization as they are. Hence, we developed an automatic mesher. First, the fractures are meshed one by one and their intersections are taken into account (Koudina et al 1998); an example is displayed in Fig.1b. Second, the space located in between the fractures are meshed with tetrahedra which are first generated from the triangles in the fractures (Bogdanov et al, 2002); this is shown in Fig.1c. It should be emphasized that these operations are fully automatic.

The porous matrix is modeled as an elastic and isotropic solid, characterized by two Lamé coefficients; the fractures possess two joint rigidities, one perpendicular and another parallel to the fractures. A pressure can be included in the fractures themselves which corresponds to the possible existence of a fluid. It must be emphasized that all the mechanical properties such as the Lamé coefficients can depend on space. Hence, the proposed approach is very wide and able to address a large variety of situations.
The external boundary conditions can be of several types. One can impose macroscopic stresses in order to homogeneize the mechanical properties. One can also address situations with specific boundary conditions such as the stresses close to a tunnel.

3. First illustrations of the general methodology
At the time where this abstract is written, the code has been implemented and has been thoroughly checked. We shall present some of these checks.

The case of an infinite fracture is displayed first in Fig.2a under the action of an imposed displacement gradient $e_{zz}$ in the direction normal to the fracture plane. The more interesting situation of spatially periodic spherical void is displayed in Fig.2b; hollow cavities are embedded in a solid matrix submitted to triaxial loading; the effective bulk modulus $K^*$ is compared to the results of theoretical analysis with an excellent agreement.

Finally, a test network containing ten fractures is shown in Fig.2c under the action of an uniaxial loading in the vertical direction. The resulting deformation of the fractures cannot be compared to any theoretical prediction, but it clearly possesses all the desired features since for instance the deformation of the vertical fracture is much smaller than the one of the horizontal fractures.

Fig.2: Aperture evolution (—) and embedding rock deformation (—)of a single fracture (a); effective bulk modulus of a spatially periodic network of spherical inclusions (b); apertures in a small fracture network under vertical loading.

4. Concluding remarks
These first studies will be developed in several directions. First, the rheology of the solid matrix will be modified and be changed into the perfect elastoplastic model and the Lemaître model. Second, the delicate question of the fracturation will be addressed. Then, the creep of the fractured medium and the evolution of its transport properties will be studied.

References
We present the results of fracture analyses carried out during the excavation for extension of the Underground Research Facility (HADES URF) at Mol, Belgium. The gallery is located in the Boom Clay Formation (Rupelian), at a depth of 224 m below surface, on the SCK•CEN-site. The research facility (underground lab) is build to study the clay’s potentials as a host-rock for long-term repository of high-level radioactive waste. Part of an extensive multidisciplinary study, comprising numerical and hydrogeological modelling, geomechanical and geochemical testing, the present study focuses on the fractures observed during the excavation work (origin, significance, geometry, kinematics, dynamics). This is justified, since the fractures in the clay form potential preferential pathways for fluid migration. In this context, the important questions of their extend (up to which distance, what is the density), of their origin (natural, or artificially induced by tunnelling), and of their nature (dilatancy, ductility) is analysed. A detailed and systematic inventory of fracture geometry, characteristics and evolution during excavation allowed a first assessment of the kinematics involved. Based on these observations, local dynamic aspects are determined. Regular sampling of the clay in function of the distance to the fractures provides a basis for the evaluation of the petrological- and petrophysical properties of the clay in relation to the fractures. A combination of these approaches (kinematic, dynamic, petrological and petrophysical variation) allows to characterise and classify the fractures, and to determine their origin and significance for local clay stability and permeability. The study is sponsored by ONDRAF/NIRAS.

The circular gallery was constructed by removing clay using a tunnel boring machine with a roadheader, and subsequently pushing an open shield (Ø 4.8 m) into the remaining clay. Behind the shield, a wedge-block system was used to support the gallery walls. In this way, an excavation rate of more than 2 m/day was achieved. Block faulting and fracture development was very intense and pervasive during the whole length (80 m) of the excavation. Three types of fractures were observed: 1. striated polished planes with shear sense indicators, called faults (slickensides for the surfaces themselves; (brittle) shear zones if
the whole (3D) damage-zone is regarded); 2. steeply dipping tension joints showing plumose structures; 3. sub-horizontal joints following the sedimentary bedding of the clay. The geometry, sense of movement and disposition of the fractures around the tunnel axis indicates that the vast majority of the structures are caused by stress concentration and stress relief induced by tunnel excavation. Additionally, dynamic parameters (orientation and shape of the paleostress ellipsoid) deduced from fault kinematics show direct relation with excavation induced local stress redistribution.

At the time of writing, clay samples are being prepared for petrological- and petrophysical analysis. At various distances from observed fault planes, several properties (including porosity, permeability and sonic wave velocity) will be measured. Petrological and micromorphological analysis of the fault and joint planes will be carried out. SEM and Backscattered Electron Microscopy and conventional petrological light microscopy of thin sections perpendicular to the planes (faults and joints) and parallel to movement direction (faults) will structurally and geometrically characterise the shear zones. This way, the deformation (particle reorientation and pattern) of the shear zones and their extend (thickness) will be determined. Additionally, the surface morphology and alteration (oxidation, mineralisation) will be characterised. The study thus combines microtectonics, macrotectonics and small-scale petrophysics to fully describe and interpret the faults and joints occurring in the Boom Clay at the level of the underground research facility for long-term disposal of high-level radioactive waste.
HYDRATION ANALYSES OF A LARGE SCALE SEAL TEST OF A CLAY POWDER/PELLETS MIXTURE

B. Valleján, A. Gens, J. Vaunat

Dept. of Geotechnical Engineering and Geosciences, Technical University of Catalunya,
C/ Jordi Girona 1-3, Building D-2, 08034 Barcelona, Spain

Keywords
Unsaturated soils, Backfill material; Swelling behaviour, Powder/Pellets mixture.

To study the response of a repository sealing in an argillaceous rock, a large scale in situ test (Shaft Sealing Test) is being carried out in the Boom clay formation at the Hades laboratory in Mol, Belgium. It consists on the hydration of a plug made with a compacted 50/50 mixture of powder and pellets of FoCa clay.

The test is the outcome of several years of research within the scope of the European Project RESEAL that has involved the characterisation of the host formation, laboratory testing of the sealing materials and an in situ small-scale test.

The plug has 2.1 m height and 2.5 m of diameter; it has been installed in an existing vertical shaft at a depth of 300 m inside the formation. Two instrumented levels were installed to measure the response of the seal to the hydration. Each level consists of displacement transducers and 3 instrumental rods. Each rod is equipped with 2 pore water pressure sensors, 4 total stress sensors to measure the longitudinal and tangential stress, one relative humidity sensor to measure the evolution of suction and 5 thermocouples distributed along the rods.

The instrumentation of the host rock includes total longitudinal and tangential stress sensors and hydraulic stress sensors for the pore water pressures. For the hydration of the shaft, several filters were installed, seven on the central tube at different levels, three at the bottom level and three at the middle. On the top, a filter inserted in a sand layer will hydrate trough the hole section. An schematic view of the filters and the instrumentation levels can be seen in Figure 1.

In this paper, an insight into the predictive capabilities of a Finite Element THM model applied to simulate the hydro-mechanical response of the seal is presented. The parameters used to describe the hydro-mechanical response of the powder/pellets mixture and of the rock were estimated from the analysis of laboratory data.

The results of the numerical simulations are compared with the available field measurements of water pressure, total stresses, displacements and degree of saturation. All the features of hydration, initial water content and compaction of the clay/pellets mixture are considered in the numerical model.

Differences are discussed with special attention to the reliable representation of coupled phenomena occurring in the powder/pellet mixture on the basis of a homogeneous material having the same dry density as the powder/pellet mixture.
Figure 1. Schematic view of the filters and instrumentation levels
TEXTURAL MODIFICATIONS OF COMPACTED MX 80 BENTONITE SUBMITTED TO HYDRATION - DEHYDRATION CONDITIONS

Y. Geraud ¹, J. Duplay ¹, G. Montes ¹, E. Priftuli ¹, J. Poisson ¹, L. Martinez ², T. Reuschlé ³

1. UMR 7517 ULP-CNRS, CGS, 1 rue Blessig, 67084 Strasbourg
2. UMR 7566-G2R, Université Henri Poincaré, 54506 Vandoeuvre-lès-Nancy
3. UMR 7516 ULP-CNRS, IPGS, 5 rue René Descartes, 67084 Strasbourg

Introduction
Up to know, the best way foreseen for radioactive waste management, is to store them in deep geological formations and to isolate them by embedding them in compacted bentonite. Many studies have been devoted to the physical and chemical properties of compacted bentonite in order to study their ability to retain radionucleides and to forecast their long term behaviour. In this work we are interested in the microscopical textural modifications of compacted bentonite MX80 and the textural behaviour of samples submitted to a hydration/dehydration cycle. For that, we use adsorption measurement, BET, Hg-porosimetry, SEM and environmental microscope (ESEM), which enables to keep clay samples in hydrated states and to proceed to dynamical studies.

Samples and experimental conditions
The MX 80 bentonite is industrial clay containing about 80% smectite, biotite and accessory minerals like iron oxides and hydroxides and carbonates. It is a low charge montmorillonite with interlayer sodium and calcium.
Measurements are performed on samples of MX 80 bentonite compacted at 4 different pressures (21, 35, 50, 64 MPa) to simulate the interval of storage conditions. Surface areas were measured by BET method using N₂ adsorption gas. ESEM observations were made during a cycle of hydration/dehydration, successively at a primary relative humidity of 5%, after hydration at 75% HR and finally after dehydration to the initial state 5% HR.
Adsorption curves were obtained by weighing samples after adsorption of water in an isotherm chamber where humidity is controlled by saturated salt solutions.

Results
Porosity of uncompacted bentonite is connected through two threshold families. First, with 2 μm size, has the porosity volume decreased with the pressure increase. The second, with 0.01 μm, is less affected by the increase of the pressure. SEM observations and Hg-porosimetry show that the pressure induces modifications of the intergranular porosity while the interparticular porosity is less modified. Macroporosity forms on intergranular network, the element shape change from tube for low pressure sample to crack for high pressure sample.
Water adsorption experiments and BET measurements show that the amount of water adsorbed does not drastically change with compaction, pointing out the micro-porosity control on the specific surface of the material. But a small decrease of the area is measured for intermediate pressures, this could localise the change in macro-porosity shape, which is also the pressure transition between compaction and brittle behaviour.
ESEM observations show clearly the compaction effect on the behaviour of bentonite MX80 submitted to hydration and dehydration. The fissures which appear at the initial dehydrated state and enlarged at 75 %HR do not recover their initial size after final dehydration. This
phenomenon is amplified when compaction increases. This is in relation with the fissures which are larger at high HR for stronger (64 MPa) compacted samples.

**Conclusion**

Structural behaviour of bentonite submitted to different confining pressure (between 0 and 60 MPa) is controlled by transformation of the shape of macroporosity network from tube to crack with the increase of confining pressure. But fluid-rock interaction surface is controlled by the micro-porosity and this parameter has a little decrease for an intermediate confining pressure. Under hydration-deshydration cycles, the strain increases with the crack content.
EXPERIMENTAL STUDY AND MODELLING OF THE RETENTION CURVE AND THE RELATIVE PERMEABILITY OF A SWELLING CLAY SUBMITTED TO TEMPERATURE

C. Imbert $^1$, E. Olchitzky $^{1,2}$, T. Lassabatère $^2$, P. Dangla $^3$, C. Gatabin $^1$

1. CEA Saclay, DEN/DPC/SCCME/LECSA, 91191 Gif-sur-Yvette, France
2. EDF-DRD, site des Renardières, BP n°1 Ecuelles, 77250 Moret-sur-Loing, France
3. LCPC, 58 boulevard Lefebvre, 75015 Paris, France

Introduction
In many concepts for deep geological repositories, compacted swelling clays are currently adopted as appropriate engineered barriers. Once installed between the saturated host rock and the container, such barrier hydrate, heat, swell and undergo stresses thereby experiencing thermo-hydro-mechanical (THM) couplings. The understanding of these couplings is a key point for the design of nuclear waste disposals. In the framework of Biot’s theory, a fully coupled model for clay barriers is presented, along with its experimental identification (retention curves at 20°C, 50°C and 80°C).

The thermodynamical and theoretical framework adopted comes from the works of Biot (1977) and Coussy (1995) on the mechanical modelling of porous media. The extension of traditional poro-mechanics to unsaturated porous media is based on the role of the capillary curve of the material.

1. Retention curves at constant temperature
The saturated saline solutions allow an exploration of a large domain of suction, from 3.29 to 366 MPa. The mass of the porous sample is regularly measured. At the equilibrium the final mass and strains are carefully determined. So the moisture content (w) and the void ratio and strains (e, ε) are known and the saturation degree (Sr) is calculated. The method has been applied to compacted samples of French FoCa swelling clay.

The first test, at 80°C; implies sorption and desorption paths. The second one, at 50°C, is only a desorption path. The influence of the temperature on the void ratio is negligible. On the other hand, the water content decreases with temperature, more particularly when Pc is lower than 100 MPa. The saturation degree is lower with temperature (figure 1).

2. Experimental measurement of liquid permeability
This method aims to determine the liquid relative permeability of a porous material, $k_{l0}$, as a function of its saturation state. It is based on both an analytical solution and on experimental measurements, at 20°C. If all the features of the porous sample are perfectly known, excepted the liquid permeability, the evolution of the mass is a function of time and liquid permeability: $M=M(t, k_{l0})$. The evolution of the mass of the sample is experimentally completely determined. Consequently, the fitting of the analytical solution to the observed experimental evolution leads to the value of $k_{l0}$ (figure 2).
**Figure 1**: Influence of the temperature on the sorption and desorption curve of FoCa clay, $Sr = f(Pc)$

**Figure 2**: Relative liquid permeability of the unsaturated compacted FoCa clay
STRUCTURAL MODIFICATIONS OF CALLOVO-OXFORDIAN ARGILLITE UNDER HYDRATION - DEHYDRATION CONDITIONS

G. Montes 1, D. Bartier 2, J. Duplay 1, L. Martinez 2, S. Escoffié 3, D. Rousset 1, Y. Geraud 1, R. Michels 2

1. UMR 7517 ULP-CNRS, CGS, 1 rue Blessig, 67084 Strasbourg
2. UMR 7566-G2R, Université Henri Poincaré, 54506 Vandoeuvre-lès-Nancy
3. LAEGO-ENSG, Rue du Doyen Marcel Roubault, Vandoeuvre-lès-Nancy

Goal of study
The argillite of the Meuse/Haute-Marne underground research laboratory is a hard rock containing 30-40% of clay minerals. In the underground laboratory where argillites will be submitted to rapid changes of these different conditions, several effects are to be considered. One of the first physical processes, extremely rapid, will be hydration and/or dehydration of swelling clays minerals. These modifications generate changes of clay structure and consequently texture of the argillite. In order to observe structural modifications of according hydration-dehydration cycles we have used an Electron Scanning Environmental Microscope (ESEM).

Observation conditions
The major advantage of ESEM is the possibility to observe geological samples in their hydrated natural state, and without preliminary preparation susceptible to modify structure samples. The method gives direct visual information inaccessible by conventional electronic microscopy. ESEM allows also working both in different Relative Humidity conditions (RH of 0 to 100%) and in a great interval of temperatures (-10 °C to 50 °C). Two types of samples are prepared, parallel to the lithology and perpendicular to the lithology. One hydration/dehydration cycle represents successively: 1. primary relative humidity of 2.5% (P = 2.3 Torr, T = 50 °C); 2. condensation of water (P = 8.6 Torr, Temperature = 8 °C) and 3. return to initial conditions (P= 2.3 and T= 50 °C).

Results
The samples observed are from the callovo-oxfordian formations in HTM 80743, HTM 983, HTM 102, HTM 02618 and EST 2159 cores. They are mainly composed of quartz (20 to 40%), calcite (15 to 40%) and clay minerals (15 to 50%). Other minerals are pyrite, dolomite, feldspars and gypsy. The clay fraction corresponds to illite (12%), illite/smectite mixed-layers (10%), chlorite (9%) and kaolinite (2%). The porosity distribution is heterogeneous and induces a weak permeability. In more clayish zones, shrinkage cracks are observed; it shows the role of hydration and dehydration on the argillite structure. ESEM observations confirm that sample are very sensitive to the hydration/dehydration cycles. In each case, it’s possible to observe on perpendicular faces to the lithology the development of fractures. These fractures evolve in function of the number of cycles. The development of fractures can be progressive or regressive. For example if a fracture appears during the first cycle, it can show a partial closing during second and third cycles. The splitting is therefore partially reversible. The growth of fractures during the first cycle is emphasized by the presence of a rigid mineral as quartz. In such case, the closing of fractures after second and third cycles is more partial because they stay opened in the clay minerals/rigid mineral interface. The observations with face sample parallel to the lithology display that a rigid mineral plays a catalyser role for the
splitting. Indeed, even on this theoretically surface more resistant to condensation/water evaporation cycles, the development of interface porosity generates splitting. The presence of a rigid mineral favours the splitting. The proportions of minerals also have great influence on the behaviour of the sample during hydration-dehydration cycles: in samples where clay minerals proportions are low (13 %) and quartz high (36 %) the cracking is less important. In conclusion, sensitivity of argillite to hydration-dehydration cycles depends directly among others, on the minerals, and particularly clay and quartz proportions, on the clay type and on the porous structure anisotropy.

This work was financially supported by Sfere (Conacyt, Mexico) and GdR FORPRO (CNRS-Andra, France)
EXPERIMENTAL STUDY OF THE INFLUENCE OF THE DEGREE OF SATURATION ON PHYSICAL AND MECHANICAL PROPERTIES IN TOURNEMIRE ARGILITE (FRANCE)

F. Vales¹, D. Nguyen Minh¹, H. Gharbi¹, A. Rejeb²

1. LMS Ecole polytechnique, 91128 Palaiseau Cedex, France
   email: vales@lms.polytechnique.fr
2. Institute of Radioprotection and Nuclear Safety, Fontenay aux Roses, France

In addition to direct mechanical perturbations, an excavation influences the hydric state of rock with regard to hydration and desiccation. The object of this study is to investigate the influence between the degree of saturation and the physical/mechanical properties for an argilite rock. Anisotropy effects are studied with samples drilled in three different directions. To understand the effects of hydric perturbations on thses shales, the Laboratory of Solids Mechanics (LMS) conducted an experimental study program to determine the effect of water saturation on the physical and mechanical properties. The correlation laws between the hydric state of the material and the mechanical properties are indispensable input data to a hydro-mechanical model.

The aim of this work is to provide physical and mechanical data that are dependent on water saturation. To obtain different water saturations (from quasi dry atmosphere to quasi-saturated ones), shale samples are put in equilibrium with controlled relative-humidity atmospheres, or hydric cures. During this hydric cure, the evolution of physical parameters (weight, length, local strains) are recorded. This gives a time evaluation of the equilibrium or transfer kinetic.

Then, for different cures, the mechanical characterisation (a compressive test with and without confinement) is performed. These compressive tests are carried out in order to attempt to establish a relationship between different mechanical parameters (elastic and failure data) and the sample saturation.
GEOTECHNICAL CHARACTERISTICS OF BENTONITE SUBJECTED TO THE THERMAL TREATMENT

Jaroslav Pacovský ¹, Lumír Nachmilner ²

1. CEG CTU, Praha
2. RAWRA, Praha

Bentonite and montmorillonite rich clays are materials the use of which is considered for construction of the engineered barrier system of a geological repository. In starting phases after burial of high level radioactive wastes or spent nuclear fuel these materials will be exposed to the elevated temperature. The highest temperature reached and a period of its action depend directly on the “age” of disposed of waste or spent fuel and on the design of disposal positions. Based on existing information, it is supposed that the temperature should not exceed the limit of some 90 °C. This may lead to a requirement for the enlargement of distances among disposed of packages and - as a result – to higher volume of the mined out rock. Therefore, a detailed investigation of behaviour of the considered buffering and backfilling materials may bring inputs not only to safety considerations but also to evaluation of economical aspects of the subsurface part of a repository. These were reasons for opening a project aiming at detailed description of the considered materials subjected to extreme thermal load. The experiments have been carried out in laboratory conditions but a large mock-up experiment (KBS 3 – like concept) was also recently commissioned. This paper summarises the result measured only in laboratory and semi-pilot plant levels.

The methods employed in determination of clay characteristics are as follows :

a) Determination of total density of soils $\rho$ (Czech standard ČSN 72 1010)
The total density of soil is defined as a ratio of its weight and total volume of a sample. The sample has natural water content.

b) Determination of dry density of soils $\rho_d$ (ČSN 72 1010)
Dry density of soil is defined as a ratio of the weight of solid particles and total volume of the sample.

c) Determination of specific weight of soil $\rho_s$ (ČSN 72 1011)
The specific weight is defined as ratio of weight of solid particles (dried at 105 – 110 °C) and their volume.

d) Determination of grain size distribution of soils (ČSN 72 1011)
Grain size curve is total line, where every point indicates what percentage from total weight of the sample is smaller than a particular diameter of grain. Two laboratory methods were used, namely: sieve analysis – sieving (on sieves of standard size) for sandy to gravel grains and hydrometer method – for silt grains based on the Stokes sedimentation formula, which give relation between grain dimension and their sedimentation in liquid.

e) Determination of water content of soils (ČSN 72 1012)
Water content of soil is defined as a ratio of the weight of water in soil and the weight of dried soil.
f) **Determination of liquid limit of soils** (ČSN 72 1014)
A clay soil becomes pasty and later liquid with the increase of its humidity. The liquid stage corresponds to stage, when the soil does not show any resistance against shearing strain. Water content on the boundary between plastic and liquid stage of soil is indicated as the liquid limit. The liquid limit is determined in standardized Casagrande’s dish.

**g) Determination of plasticity limit of soils** (ČSN 72 1014)
Water content on the boundary between plastic and solid stage of soil is indicated as plasticity limit.

**h) Characteristics of cohesive soil** (plasticity index, rate of consistency, rate of liquid, index of colloidal activity of clay) are determined on the base of consistency limits.

**i) Uniaxial strength test** (European Standard EN 1926)
A specimen is exposed to the load in the direction of compaction (during fabrication).

**j) Triaxial strength (three-dimensional)**
A cube-shaped sample is loaded by pressure in three directions or a cylindrical sample is loaded by chamber pressure and by axial load.

**k) Thermal characteristics**
Thermal conductivity coefficient, specific volumetric thermal capacity and temperature of materials were measured with use of changeable needle and areal probes, based on processing responses to impulses of thermal flow into an analysed material.

**l) Determination of sorption (hydration) heat**
A hydration heat characterises ability indicate a tendency of bentonite to adsorb water (and to dissolve an ion). The adsorption on bentonite surface can prevent to spread of contaminant in around geosphere. Adsorption is one of the main indicators for characterization of bentonites.