# GEOMECHANICAL RESEARCH FOR RADWASTE DISPOSAL IN DEEP CLAYS - *FIRST RESULTS AND PROSPECTS*

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## ABSTRACT

The aim of the geomechanical research program for underground radioactive waste disposal is double: realizing a geotechnical cartography of the sedimentary sites and elaborating mechanical-transports coupled models for the short, middle and long term behavior of these materials. In the first part of this paper, statistic analysis between physical and mechanical properties of nearly 1000 sample of argillaceous rocks is presented. A geomechanical spectrum is proposed as a classification of mechanical behavior with respect to dry density value. The second part of this paper is devoted to experimental studies of time behavior of a hard claystone (argillite from East of France). Special tests based on radial extension have been carried out to characterize middle and long term behavior of the material. Preliminary results indicate that this rock exhibits noticeable time dependent behavior.

## INTRODUCTION

In the framework of feasibility studies of radioactive waste disposal in France, geomechanical studies of argillaceous rocks have been undertaken since 1994 on samples, in surface laboratories, and in deep boreholes. The objective of these studies is to assess whether two deep clay formations, argillites in the East of France and siltites in the South of France, have right properties to be a disposal for long lived high level radwaste. Among these properties, geomechanical ones are of particular importance for the construction as well as the safety assessment of the disposal.

The geomechanical research program has two objectives: to propose a geotechnical cartography of the geological medium and to develop coupled mechanics-transport models. This first objective allows to choice the best section for the disposal and to optimize the conception, the second leads to assess the reversibility and the safety of the disposal. In this paper, the results of two recent studies are presented to illustrate these two objectives.

Firstly, in geomechanics it is impossible before construction to access the detailed geomechanical properties of the adjacent rock mass, so it is necessary to find a physical parameter, easy to identify and representative of the physical and mechanical properties of the material. For argillaceous rocks, the mechanical behavior is not only governed by the void ratio but also by the very complicated process of lithification and the related physical and chemical transformations, specific to each site configuration. Nevertheless, we believe that common features can be encountered between these rocks in spit of the discrepancies of the present burial depth and the mineralogical content.

During the past 10 years, ANDRA has been surveying deep argillaceous sites in France and managing in partnership with other countries, underground laboratory experiments in clay formations : Boom clay (Mol, Belgium), Opalinus clay (Mont-Terri, Switzerland). Physical and mechanical tests have been carried out, by ANTEA, over nearly 1000 samples including the aforementioned French argillaceous rocks and those from other sites. This large experience had to be valued by a systematic statistical analysis in order to find representative parameters to characterize mechanical properties of these argillaceous formations.

Secondly, to explore the middle term and long term behavior of the mentioned French argillaceous rocks, creep and relaxation tests have been carried out. Even if these argillaceous rocks can be considered as hard clay, even hard rocks, since their instantaneous compressive strength ranging from 10 MPa up to more than 90 Mpa. However, their time dependent properties have significant effects on the long term resistance, especially for the argillites formation in the East of France. That lets to rise questions for long term behavior of galleries at great depth, with progressive wall closure, loading of the support system, together with a progressive development of a disturbed zone around the gallery where permeability may be increased by several orders. The permeability of adjacent rock is the key question for the tightness of geological barrier.

One major objective of time dependent behavior study is to calculate the long term strength of the rock, according to a "limit curve" or "limit strength concept" proposed by Berest et al in 1979. The second objective is to describe how instantaneous state proceeds toward a final one with time. So, the second part of this paper shows the preliminary results of relaxation tests, which are performed in specific loading conditions similar to that remaining in the adjacent rock mass of the tunnel. These tests illustrate a limit curve concept and indicate that the argillites exhibit a noticeable delayed behavior.

## COMPOSITION OF THE DATABASE

For ten years, geomechanical experiments have been carried out to explore the mechanical behavior of argillaceous rocks under a lot of stress and hydraulic conditions (monotonous and cyclic drained and undrained triaxial tests in compression and in extension, creep tests under triaxial stresses, compression and swelling tests under oedometric stress conditions). These often sophisticated laboratory experiments have been systematically preceded by an identification of physical parameters like wet and dry densities, water content, carbonate content, and P and S-wave velocities and sometimes by uniaxial compression or extension tests that provide compressive or tensile strengths.

The well surveyed argillaceous rocks concerned by those experiments are:

- the Callovo-Oxfordian and the Toarcian-Domerian argillites of Montcornet (Aisne, France),
- the Callovo-Oxfordian argillite of the so-called Est Site (Meuse, France),
- the Albo-Cenomanian siltstone of the so-called Gard Site (Gard, France),
- the MDPA marl ( Haut-Rhin, France).

- the Rupelian Boom clay (Mol, Belgium),
- the Aalenian Opalinus clay (Mont-Terri, Switzerland),
- the Cattenom clay (Moselle, France),
- the Toarcian Tournemire argillite (Aveyron, France)

**Tab. I. General parameters of the argillaceous rocks (922 data)**

| Sites \ Parameters | Relative proportion (%) | Depth (m) | Carbonate content (%) | Dry density (g/cm3) |
|---|---|---|---|---|
| Est Site | 28.3 | 350-500 | 23 - 42 | 2.21 - 2.33 |
| Montcornet | 26.7 | 327-460<br>685-850 | 6 - 34<br>3 - 14 | 1.97 - 2.60<br>2.06 - 2.26 |
| Gard Site | 20.7 | 390-775 | 15 - 35 | 2.32 - 2.48 |
| Mol | 8.1 | 210-240 | 0 - 3 | 1.61 - 1.78 |
| MDPA | 6.9 | 500-540 | 48 - 53 | 2.38 - 2.42 |
| Mont-Terri | 6.7 | 275 | 8.5 - 28 | 2.22- 2.33 |
| Tournemire | 2.3 | 250-370 | 11.5 - 35 | 2.45 - 2.55 |
| Cattenom | 0.2 | 25 | 6 - 8.5 | 2.15 - 2.28 |

These argillaceous rocks are covering a wide range of burial depths and mineralogical contents and, consequently, a wide range of porosity and dry densities as showed in table I.. The whole geomechanical database is nearly containing 1000 samples for which we have got at least basic physical parameters and some mechanical properties. The types of the available data are very different from one site to another, due to the different objectives and origins of the data. We have not kept the mechanical properties provided without any related physical parameters. The geomechanical database was easily conceived as a big table with the following topics; name of the site, location parameters, geological unit, physical properties, mechanical characteristics and data files of mechanical test outputs. The table I shows the relative proportions of samples site by site.

## SPECTRUM OF PHYSICAL PROPERTIES OF THE ARGILLACEOUS ROCKS

We would like to answer the following question: Is there any physical parameter governing the mechanical behavior of the argillaceous rocks? In many cases, the history of the stress path of deep sedimentary rocks can be summarized to a normal sedimentation process without any significant incidence due to erosion phases. Then, in that simplified scheme, the history of the stress path can be well represented by the burial depth i.e. by the present in-situ mean effective stress. The history of the lithification process can be more complicated but we assume that the mineralogical content and the void ratio are some significant outcomes of this process. It must be noticed that the void ratio is both an outcome of the lithification process and of the history of the burial depth. In other respects, it exists a simple relationship between the void ratio e and the dry density $\rho_d$ such as: $e= \rho_s/\rho_d -1$, where $\rho_s$ is the density of solid particles. Moreover, it is often observed that the dry density increases with an increasing carbonate content and a decreasing clay content. Then, we propose to consider the dry density as a candidate parameter which can explain the main features of the mechanical behavior of argillaceous rocks.

A monotonous relationship between the water content and the dry density is clearly observed for all the samples and is well fitted with the theoretical hyperbolic curve of the saturated materials, such as: $w_{sat} = 100\ \rho_w\ ( 1/\rho_d\ - 1 / \rho_s)$ with $\rho_s$ equal to 2.65 g/cm$^3$ or 2.7 g/cm$^3$. Then most of the samples are saturated or nearly saturated. A monotonous non linear trend between ultrasonic P-wave velocity values and the dry density is observed. Moreover, we find that the P-wave velocity is nearly constant around 1500 m/s for $\rho_d$ less than about 2.0 g/cm$^3$ but the P-wave velocity highly increases for $\rho_d$ greater than this approximate dry density value. This is an indicator of a radical change of mechanical behavior between these two domains of $\rho_d$ values (Heiz J.F. et al 1998).

## DRY DENSITY AND THE GEOMECHANICAL SPECTRUM

Uniaxial compressive strengths and related deformability modulus are very dependent of the dry density as shown in Figures 2a and 2b. As for P-wave velocity, two domains can be clearly defined with a boundary dry density value ranging from 2.1 to 2.2 g/cm$^3$, depending on the mechanical parameter. Similar results have been proposed by Serratrice & Durville (1997). Very steep slopes for the higher dry density values than this limit value, indicate that a small change of the dry density can explain a large variation of those mechanical properties which are very important to design structures in such argillaceous rocks. So, we propose to identify classes of mechanical behaviours based on the dry density values of the argillaceous rocks. Two main classes are distinguished with a boundary value assumed to be 2.15g/cm$^3$.. Considering that the uniaxial compressive strength is changing a lot with an increasing dry density for $\rho_d$ greater than 2.15g/cm$^3$, we propose to distinguish two subclasses with another boundary value equal to 2.35g/cm$^3$.. Consequently, three classes are created: class 1 (<2.15g/cm$^3$), class 2 (2.15-2.35g/cm$^3$) and class 3 (>2.35g/cm$^3$).

Undrained and drained compression triaxial tests have been performed on argillaceous rocks of the three classes with a consolidation isotropic effective stress $\sigma'_c$ close to the estimated in-situ mean effective stress $\sigma'_z$ (ranging from 4 to 8.5MPa, depending of the depth of sampling). Differences of mechanical behavior can be noticed. The less dense material of class 1 exhibits a rather ductile behavior with contractance (increase of pore pressure) up to the sample failure and without strain softening after the deviatoric peak stress. Unlike the denser material (class 3) exhibits a brittle behavior with a low vertical strain of failure (less than or about 1%) with a contractant phase (increase of pore pressure) followed by a phase of dilatancy (decrease of pore pressure) before the sample failure. A gradual change of the mechanical behavior of the three families can be noticed by comparing drained and undrained triaxial test results with increasing consolidation effective stress.

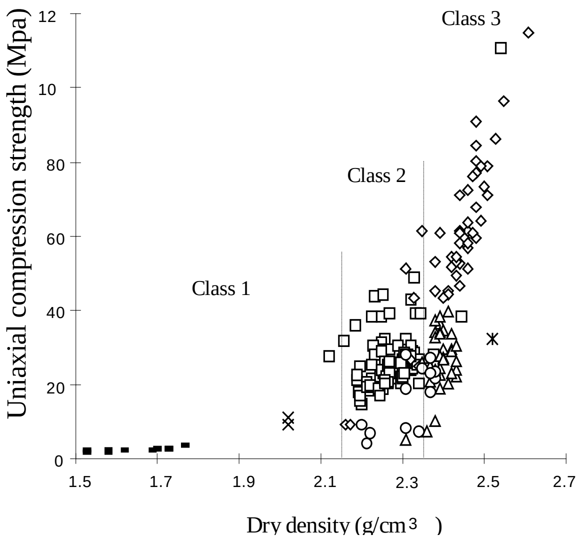


Fig. 1a. Uniaxial compression strength vs. dry density for all sites.

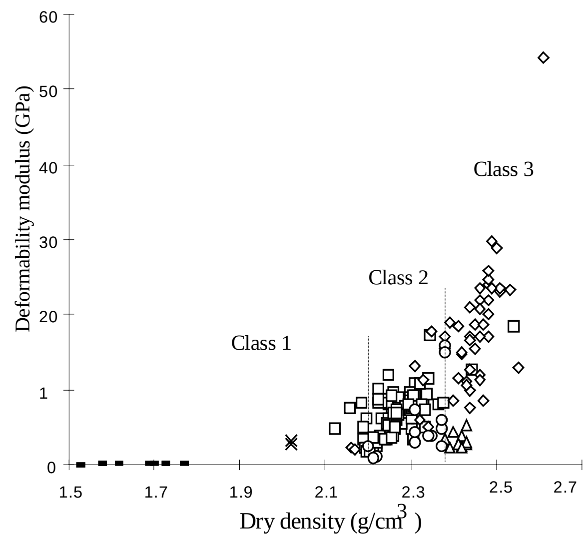


Fig. 1b. Deformation modulus vs. dry density for all sites.

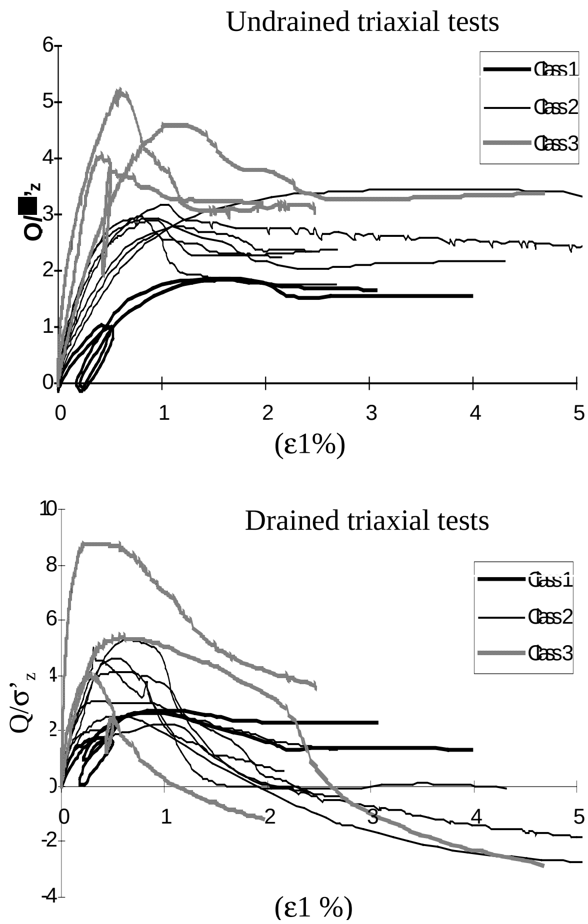


Fig. 2. Results of drained and undrained triaxial tests for argillaceous rocks of the three classes with $\sigma'_c$ - $\sigma'_z$ (ranging from 4 to 8.5 Mpa, depending on the depth of sampling)

Different classes of mechanical behaviors of argillaceous rocks can be defined and form a geomechanical spectrum with the main features expressed as ranges of predominant values in the table II.

**Tab. II. Characteristic values of the argillaceous rocks of the geomechanical database**

| **Properties** | $\rho_d$ < 2,15g/cm$^3$ | 2,15 < $\rho_d$ < 2,35g/cm$^3$ | $\rho_d$ > 2,35g/cm$^3$ |
|---|---|---|---|
| Wsat (%) | > 9,5 | 5,5 à 9,5 | < 5,5 |
| Porosity (%) | > 20 | 13 à 20 | < 13 |
| P-wave velocity (m/s) | < 2000 | 2000 à 3000 | > 3000 |
| Rc (MPa) | < 15 | 15 à 35 | > 35 |
| E (MPa) | < 3000 | 3000 à 10000 | > 10000 |
| Behaviour in triaxial test | ductile | ductile/brittle | brittle |
| Q/σ'z (for σ'c~σ'z) drained triaxial tests | <2,5 | 2,5 à 3,5 | > 3,5 |
| Cc (at 50MPa) | > 0,15 | 0,05 à 0,15 | < 0,05 |

## TESTING PROCEDURE FOR STUDY OF TIME DEPENDENT BEHAVIOR

Another part of the research program is the characterization of the long term behavior of the studied materials. The argillaceous rocks of Est Site (argillite) and Gard Site (siltstone) appear as hard rocks, ranging typically from 10MPa to more than 90MPa.. However, their time dependent properties can induce long term resistance lower than the short term one.

Having regard to the complex nature of the rock behavior, it was decided to perform tests in specific conditions of loading as close as possible from actual one which prevails around the tunnel since the first instant of its construction. The following text presents for illustration, some preliminary tests performed on a Callovov-Oxfordian argillite from the East of France. The mineralogy content of this rock typically includes 40% clay, and 20-30% carbonates, and a some 4-6% water content. The rock formation appears as a thick layer situated at 420-526m depth.

Although carefully sampled and well conditioned, hard marls are known to be very sensitive to small water content variations, which may lead to scattering of results; this complexity adds to the mechanical behavior one, which results partly from brittle rock behavior interfering with its delayed response.

The tests are undertaken in a classical triaxial cell. The loading path at the wall of the gallery can then be simulated. In a first stage, the sample is confined up to hydrostatic pressure $P_o$ at a conventional rate of 1MPa/mn. Then a radial extension test is produced, by decreasing the axial stress and increasing lateral pressure so that the mean value of the extreme stresses remains constant and equal to initial confinement $P_o$.. For a 500m deep tunnel, the vertical geostatic stress can be taken as a reference and estimated to 12.5MPa, so pressure $P=P_o$ for triaxial tests were chosen in the interval 5MPa, 30MPa, to take into account an eventual anisotropy of stress state with lateral coefficient up to Ko=2.4.

It can be noticed as far as excavation methods are considered (e.g. full face tunneling), that loading rate should be very low, contrary to classical drill and blast methods. Evaluation of such rates could be obtained from a detailed numerical analysis of the strain rates generated around an advancing tunnel front. However, a very rough evaluation can be made. Suppose the distance of front face influence of the tunnel lays typically over a distance of three tunnel diameters, so that the deconfining pressure can be considered to decrease until zero from its initial geostatic stress value $P_o$ on this distance, according to convergence confinement method. Typically, if the mean advance rate is 3m per hour for a 10m diameter tunnel, with $P_o$=25MPa, the deconfining rate would be 2.5MPa/h, which corresponds to $10^{-7}$/s deformation rate for a typical Young's modulus of 6000MPa.

Two kinds of tests can then be proposed :

- constant axial strain rate test, which have been performed for 9.5 $10^{-7}$/s to 9.5 $10^{-9}$/s strain rate. The latter test would require twelve days. The mean stress remains constant during the tests. Lower strain rates would be possible but require longer time which would require a good control of the environmental temperature in the room. Indeed, theoretically, a limit curve would require infinitely low strain rate, but its determination by this means would be problematic.

- multiple relaxation test. This test is more stable than classical creep tests on such rocks, and is also known to allow for much time saving, as equivalent rheological states to creep loading can be reached for a much lower duration (Lemaitre, 1970). During the test, axial strain is fixed, the mean stress remains always constant during the tests. Another advantage of this test is that relative results can be provided (e.g. loss of strength), which would be interesting in case of scattering.

## RESULTS OF CONSTANT STRAIN RATE TESTS

These tests allowed to compare evolution of the stress strain curve with longitudinal strain rate, and to have indications on damage or fracture patterns.
Two deviatoric stress $\Delta\sigma_1 = \sigma_1 - P_o$ vs longitudinal deviatoric strain $\Delta\varepsilon_1$ curves are shown respectively for $d\varepsilon_1/dt$ = 9.5 $10^{-7}$/s and $d\varepsilon_1/dt$ = 9.5 $10^{-9}$/s for a mean pressure $P_o$ = 25MPa (Figure 3). These curves are representative of the general trends observed at any pressure $P_o$.

It can be noticed that the shape of the two curves is similar, although the lower strain rate one is not so smooth, due to sensibility of the LVDT measurement to external temperature variations during the thirteen days testing, as temperature of the room is not regulated, and was submitted to 2°C variation per 24 hours.
The average loss of deviatoric strength when strain rate is decreased by one hundred times, is about 15%.
However, this holds only about a threshold value of which can be estimated about 8-10MPa ($\Delta\sigma_1$), since the curves seem to be identical under this limit. This limit appears as a viscoplastic yield stress, to be compared to 17-20MPa maximum stress attained before breakage.

In the case presented here ($P_o$=25MPa), fracture occurs without strain softening, by a sudden drop of the deviator, for a typical deformation of about 1%. However, for lower confinement pressure

fracture may not occur until the deviatoric stress has completely vanished. For example, one breakage was obtained over two tests performed for $P_o$=12.5MPa.
These fractures are extension planes roughly perpendicular to the axis of the sample with a rugged "feather like" aspect. Such fractures seem to be representative of fractures parallel to the wall observed in tunnels driven in claystones and in some hard rocks.

## RESULTS OF MULTIPLE RELAXATION TESTS

With reference to previous remarks, and to allow for comparison with the former tests, relaxation tests are operated by steps at differents axial strain amplitude obtained at constant strain rate of 9.5 $10^{-7}$/s corresponding to the quickest strain rate in the former tests. This slow rate was also prescribed in order to avoid too high deviatoric stresses, eager to cause an undesirable damage of the rock. This preliminary loading curve was considered as "instantaneous curve" for the relaxation tests, which means that viscosity relative to higher rates are disregarded, as far as middle term to long term effects are concerned.

Relaxation tests were performed for each sample for three deformations, each relaxation lasting 24 hours.
It has been first verified that no noticeable relaxation did occur for 2.3 $10^{-3}$ strain, which corresponded practically to the 8-10 MPa deviatoric stress, and confirmed the "viscoplastic" nature of that limit, as guessed from the former constant strain rates.

Figure 4 shows 24 hours relaxation tests performed for two larger strains, 3.3 $10^{-3}$ (step 2) and 4.7 $10^{-3}$ (step 3) showing respectively an increase of deviatoric stress of 30% and 51%, which is more than the 15% obtained with the constant strain rates .

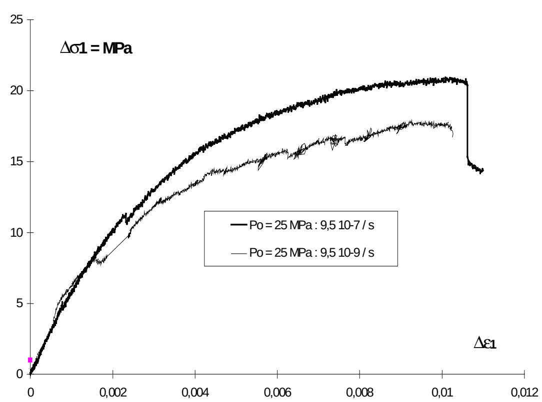


Fig. 3: Deviatoric stress $\Delta\sigma_1$ vs longitudinal deviatoric strain $\Delta\varepsilon_1$ during constant strain rate with constant $\sigma_m$ =25MPa

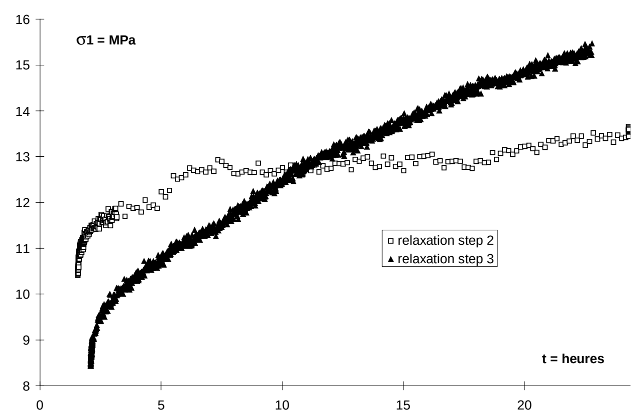


Fig. 4 Relaxation tests performed at 3.3 $10^{-3}$ and 4.7 $10^{-3}$ deformation, 24 hours duration

Moreover, the shape of these two relaxation curves are not similar, the latter one seems still far from stabilization after 24 hours relaxation. Dilatancy only occurs during the latter loading phase, which would have caused a preliminary damage of the rock and interfere during the relaxation. This fact should however be confirmed in the future.

## CONCLUSIONS

On the basis of the physical and mechanical characterization of more than 1000 argillaceous rock samples, it has been shown that the dry density seems to be a suitable parameter accounting approximately for histories of the stress path and of the lithification process which govern mainly the present mechanical behavior of argillaceous rocks. Moreover, monotonous non linear trends have been pointed out between the dry density and some mechanical characteristics like the uniaxial compressive strength. This can satisfy the following ambitious and rather caricatured remark: give me the dry density of an argillaceous rock and I shall give you its physical and mechanical properties.

The analysis of the different correlations has also allowed to define different classes of mechanical behaviors of argillaceous rocks. These classes form a geomechanical spectrum with the main features expressed as ranges of predominant values presented in the table II. The dry density seems

to be a useful index to predict the axial strain of failure for the class 1 and the shear strength for the other classes.

The preliminary tests in special condition close to in-situ stress path for the French argillite indicate that this rock exhibits a relatively important time dependent behavior. Constant strain rate tests have shown that extension fractures parallel to the axis of the sample occur for a typical 1% axial deformation, even for large pressures ($P_o$ = 25MPa). This kind of fractures is comparable to those observed in galleries. However, for lower pressures (the limit would be about 12MPa), no fracture occurred after the deviatoric stress has completely vanished.

The limit curve concept has been well demonstrated in this context, by comparing constant strain rate tests with relaxation tests under radial extension stress path.

Relaxation tests appear to be practical and well suited for approximating the middle term to long term curve. 24 hours relaxation tests have shown a decrease of deviatoric stress by more than 50%, , the different relaxation curves observed may be imputed to dilatancy occurrence. Results obtained so far show that long term deviatoric yield stress should be less than 50 to 60% from the maximum load attained during a "short term loading" (e.g. typically $10^{-7}$/s strain rate). However, the relativity of the "limit strength" concept must be noted, since the stabilization of relaxation curves is not absolute and depends on the duration of the test, on the sensibility of the experimental devices and on the control of the stability of the environmental conditions.

### PROSPECTS

The future geomechanical research program will focus on the following fields :

- Underground geomechanical tests,
- Characterization of initial hydraulic properties and its evolution under mechanical loading,
- Characterization of hydro-mechanical coupling parameters, i.e. Biot's coefficient, Biot's modulus,
- Elaboration and validation of mechanics-transport coupled constitutive models,
- Numerical modeling of coupled mechanics-transport phenomena.

These studies have three objectives: optimization of disposal conception, safety assessment and reversibility of the disposal.

An underground laboratory will be constructed in an argilite formation situated in the East of France in 2001. A series of geomechanical tests are planned. Characterization of mechanical and hydraulic initial states, studies of long term thermo-hydro-mechanical coupling behavior of rock mass are principle goals of those mechanical tests. Since the studied formation is a typical poro-plastic material, visco-plastic deformation is significant even in short time. So interpretation of all mechanical and hydraulic tests have to consider the coupling effects.

Before its construction, constitutive models of thermo-hydro-mechnical coupling, based on experimental results obtained on samples, will be applied for the conception and the establishment of the methodology of in-situ test. The evolution of stresses and pore pressure in the adjacent rocks can be assessed, in order to plan the dimension of the experiment, to choice sensibility of the sensors and the detector, to locate these instruments.

During the in-situ tests, the studies will focus on the validation of proposed coupling models. Meanwhile supplementary hydro-mechanical tests will be carried out on samples with large size in order to study the scale effect on the hydro-mechanical properties.

We have to assess the risk of extrapolation of some experimental results (in-situ or in laboratory) to long term (i.e. more than several thousand years). The study will be undertaken by a set of numerical modeling in order to carry out a sensitive study of rheological models.

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