Repository Drift Backfilling Demonstrator

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ABSTRACT

The "Backfilling Demonstrator" is one of the technological demonstrators developed by Andra in the framework of the feasibility studies for a geological repository for high-level long-lived (HL-LL waste) within a clay formation. The demonstrator concerns the standard and supporting backfills as defined in Andra's 2005 design. The standard backfill is intended to fill up almost all drifts of the underground repository in order to limit any deformation of the rock after the degradation of the drift lining. The supporting backfill only concerns a small portion of the volume to be backfilled in order to counter the swelling pressure of the swelling clay contained in the sealing structures.

The first objective of the demonstrator was to show the possibility of manufacturing a satisfactory backfill, in spite of the exiguity of the underground structures, and of reusing as much as possible the argillite muck. For the purpose of this experiment, the argillite muck was collected on Andra's worksite for the implementation of an underground research laboratory. Still ongoing, the second objective is to follow up the long-term evolution of the backfill.

Approximately 200 m^3 of compacted backfill material have been gathered in a large concrete tube simulating a repository drift. The standard backfill was manufactured exclusively with argillite. The supporting backfill was made by forming a mixture of ⅓ argillite and ⅔ sand. Operations were carried out mostly at Richwiller, close to Mulhouse, France.

The objectives of the demonstrator were met: an application method was tested and proven satisfactory. The resulting dry densities are relatively high, although the moduli of deformation[1] do not always reach the set goal. The selected objective for the demonstrator was a dry density corresponding to a relatively high compaction level (95% of the standard Proctor optimum [SPO]), for both pure argillite and the argillite-sand mixture. The plate-percussion compaction technique was used and proved satisfactory. The measured dry densities are higher than the 95%-SPO objective. The implementation rates remain very low due to the experimental conditions involved. The metal supply mode would need to be revised before any industrial application is contemplated.

The Demonstrator Program started in August 2004 and is followed up today over the long term. With that objective in mind, sensors and a water-saturation system have been installed.

INTRODUCTION

Backfills will be set in place during the closure of the shafts and of the drifts of the underground repository. According to the concept presented by Andra in its 2005 feasibility case, the role of those

1. In this document, the term "modulus of deformation " encompasses both the non-consolidated and overconsolidated states of the backfill. It consists of an elastic behavior (non-consolidated state) or close to it (a normally consolidated state) without any significant plastic deformation associated with crushing.

backfills is essentially mechanical and consists in limiting ground deformations and in countering the deformations in the sealing structures made of swelling clay. Such a mechanical role requires the backfills to withstand a certain resistance to deformation. That resistance may result from the rigidity of the backfill (the densest possible backfill would then be sought with a high Young's modulus and a high coefficient of friction) or from its swelling capability during hydration (the purpose would then be to increase the content of swelling minerals, such as smectite).

Andra's purpose was to manufacture backfills and set them within a demonstrator simulating a repository drift. The program and the main results of that experiment are described below.

OBJECTIVES OF THE BACKFILL DEMONSTRATOR

Initial objectives

The first objective of the Demonstrator was to show that it was possible to develop a suitable backfill material from the Callovo-Oxfordian argillites found on the Meuse/Haute-Marne Underground Research Laboratory Site (with potential additives, as specified). The second objective was to prove that it was possible to set that backfill within a small-size underground drift. The third objective was to demonstrate that the set backfill met the required specifications against the extension of the excavation-damaged zone (EDZ) on the drift wall (standard backfill) and behaved satisfactorily against the thrust of a swelling-clay core (supporting backfill).

Transposition of objectives in concrete terms

Andra reflected the above-mentioned initial objectives in the specifications [1] in the following quantified form:

- A 20-MPa modulus of deformation module (Young's modulus under small-loading conditions before saturation);
- Limiting any void at the vault level to 3 cm.

In addition, specifications required an argillite content at least equivalent to 80% of the mixture (*i.e.,* with the additive content limited to 20% in weight).

Specifying an elastic-modulus value has the merit of providing a criterion that refers to the function of the backfill in Andra's concept. It should be noted that the function of the backfill is primarily to counter any deformations within the surrounding rock under repository conditions (loading after rupture of the drift lining). However, using a single modulus value is arbitrary and tends to hide the non-linear behavior of the backfill. In addition, due to practical reasons[2], that criterion at the demonstrator scale may only apply to the backfill after being set in place and consequently does not deal with post-saturation evolutions.

The selected value of 20 MPa was taken from a previous study [2] on the wall damages of a backfilled drift. In that study, the backfill was modeled by an elastic material whose modulus increases with the applied load, according to the following expression:

$$E = K\,(1 + \sigma / p_a)^{0.45}$$

where E is the Young's modulus of the backfill under stress, σ; K is the Young's modulus of the backfill under no stress (MPa); σ is the confinement stress (MPa) and p_a, atmospheric pressure (0.1 MPa). A high value for the backfill modulus helps to maintain a certain thickness of the non-damaged argillite around the drifts. The backfill modulus during installation, K, must be as large as

2. Since the saturation times for the backfill are important, it is therefore impossible to access the saturated modulus before months of imbibition have passed.

possible: the study leads to a minimum value of 20 MPa for structures located at a depth of 630 m (maximum depth contemplated) and a minimum value of 10 MPa for structures located at a depth of 500 m (reference depth). Those values incorporate a safety coefficient of 2. The selected value of 20 MPa concerns the backfill over the long term (*i.e.,* saturated). However, laboratory tests have shown that the moduli dropped during imbibition. Strictly speaking, it would have been advisable to establish a margin in order to specify the unsaturated backfill of the demonstrator. Nevertheless, the integration of safety coefficients, the discarding of argillite healing together with the practical problem of achieving a stiff backfill led Andra to maintain the 20-MPa criterion for the unsaturated backfill.

New objectives during the study

Based on the objective of the 20-MPa Young's modulus, Andra and its suppliers focused on defining an easily controllable objective under worksite conditions: a dry density was selected for the compacted backfill. That objective is simple and unambiguous. Its minimum value lies between 1.7 and 1.8 t/m^3, and represents a compromise taking into account the gap in relation to the dry density of the argillite in place (in the order of 2.3 t/m^3) and to the accessible compaction energies. A dry density ranging from 1.7 to 1.8 t/m^3 corresponds to a compaction energy in the order of 95% SPO.

Supporting backfills constitute a specific case with slightly different objectives: the local character of those backfills allows for the addition of large amounts of exogenous materials, while the role of supporting backfills requires higher mechanical features than those for standard backfills. A friction angle in the order of 25° is compatible with a length of supporting backfill equal to five drift diameters, which corresponds approximately to the block diagrams selected by Andra in 2005 (Figure 1).

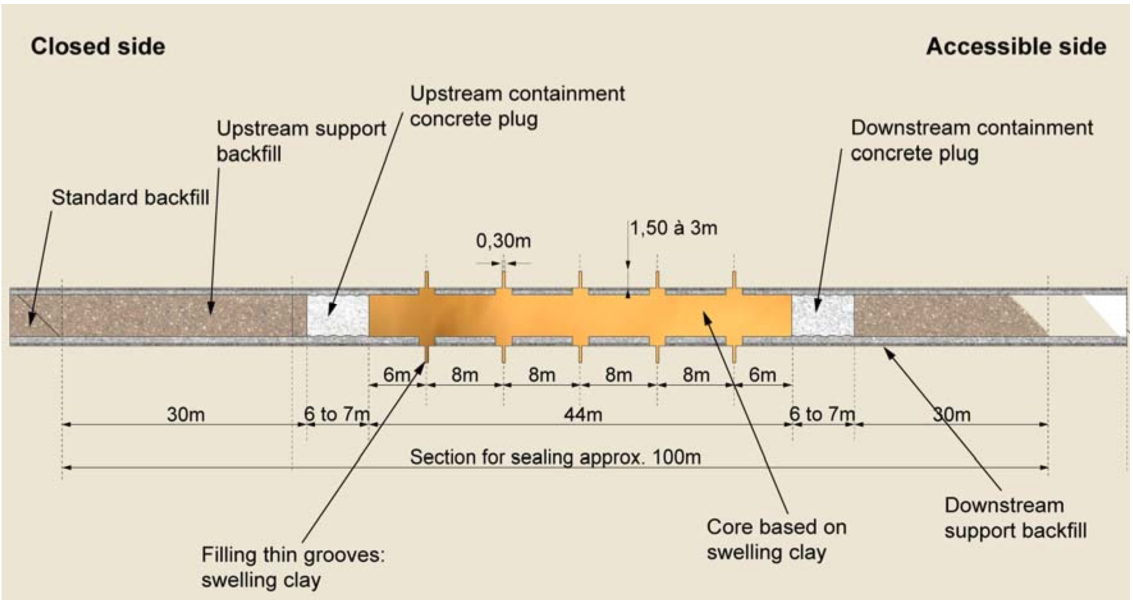

Figure 1. Block diagram of drift sealing (*Dossier 2005* type).

Concretely speaking, Andra and its suppliers have endeavored to define a formulation that would maximize the quantity of sand (which increases friction), while preserving a certain cohesion that ensures the stability of the slope. Once that formulation was defined, the dry density corresponding to 95% SPO was measured in a laboratory. The supporting backfill was then set in place according to the same processes involved with the standard backfill. Lastly, the bearing characteristics of that backfill were checked, especially by plate-loading tests.

Over a much longer term, the demonstrator must help to characterize the evolution of the backfill when submitted to saturation (forced saturation in the framework of the test, simulating the saturation of the backfill by the waters of the geological medium). In fact, the saturation of the backfill tends to generate dilatation due to the loss of capillary forces and the swelling of certain clay minerals (contained in Callovo-Oxfordian argillites), but may also inversely induce subsidence phenomena. Those phenomena are likely to occur when the backfill is being loaded (when the capillary forces have already disappeared). A saturated and loaded backfill is therefore submitted to two opposite trends (swelling/subsidence). Swelling will dominate the residual behavior of the backfill in proportion to its density and richness in swelling minerals.

It should be noted that such a long-term objective did not appear among the initial objectives. Consequently, the Demonstrator Program had to be modified in order to incorporate a saturation phase with a view to assessing the swelling character of the backfill set in place.

BACKFILL-COMPACTION DESIGN

Origin of the material

The backfill consists of 400 m3 of Callovo-Oxfordian argillite muck from the Meuse/Haute-Marne Laboratory Site. Since the shaft was sunk shortly (a few weeks) before the muck was collected, the material had not enough time to mature in the stockpile. The collected argillite has a grain size of 0/400 mm and a water concentration varying between 5 and 7%. Maturation was achieved by fragmenting the material with a pulvimixer (0/60-mm grind) and by exposing strips of it to rainwater.

In addition, the argillite was mixed with calcareous sand from a quarry in order to constitute the supporting backfill.

Initial characterization of the reworked pure argillite

The main results of the identification tests carried out on reworked pure argillite are presented below [3].

The concentration in natural water, w_{nat}, varies between 5.4 and 6.5%. The particle-size distribution before compaction on a 0/20-mm fraction shows a high concentration of fine particles (smaller than 80 microns), equal to 38.1%. The characteristics of the Standard Proctor[3] are as follows: w_{nat} = 6.8%; w_{SPO} = 14.2% and ρd_{SPO} = 1.835 t/m^3 .

Those results generate the following comments:

- The material consisting of reworked pure argillite before compaction is governed by its fine fraction (fines > 35%), which makes it theoretically a water-sensitive material (*i.e.,* likely to induce strong variations in its bearing during imbibition);
- The ratio between w_{nat} and w_{SPO} is 0.5, which classifies reworked argillites among “very dry” materials requiring a significant humidification before being set in place;
- The dry-density value of reworked pure argillite at SPO would make it a very suitable material for conventional earthworks. Its concentration is moderate (well under 20%), which is very favorable.

3. *Standard Proctor:* standardized test consisting in compacting a sample within a mould, with a standardized energy (rammer weight, drop height and number of standard strokes); SPO: Standard Proctor Optimum: maximal compactness achieved during a series of Standard Proctor tests for various water concentrations; to the SPO is associated a couple consisting of water-concentration (w_{SPO}) and dry density (ρd_{SPO}).

The characterization work was completed by oedometric tests, which are used to calculate an oedometric modulus (*i.e.,* an elastic deformation modulus within the confined space of a mould). Since the objective in terms of the Young's modulus is 20 MPa, the oedometric modulus being sought is in the order of 27 MPa (confinement effect). In addition, that objective is increased by 20% (32 MPa) in order to provide a security margin between the worksite and the laboratory.

Oedometric tests were performed on previously compacted samples. Various compaction levels were tested, expressed in dry-density SPO percentages: 85, 90, 95, 100 and 105%.

The oedometric modulus increases with loading until the latter reaches a threshold value. At that loading value, the oedometric modulus drops sharply, then rises when loading increases again. That loading threshold corresponds to the acquired preconsolidation stress during the compaction of the sample.

Those results call for several observations:

- Compaction helps to achieve a better initial modulus and minimizes the drop of the modulus when the preconsolidation stress is reached; consequently, the compaction level has an impact on the rate of argillite deformation;
- Even at the highest energies, the initial moduli remain below the 32-MPa objective;
- "Overconsolidated" moduli are considered satisfactory at 95% SPO, as long as the material is slightly hydrated.

Certain oedometric tests have helped to compare the backfill moduli to different water concentrations with a view to optimizing the conditions for setting the backfill in place. Those tests have shown a rigidification of the material when it is relatively dry. Nevertheless, rigidification is offset by subsidence during imbibition. Consequently, it is recommended to use materials with a water concentration equal to that of the optimal Proctor, or even wetter, in order to limit subsidence risks during imbibition.

Tests on various formulations

Various alternative formulations were tested [3]. Some of them were more intended for standard backfills, as in the case of argillite/bentonite and argillite/lime mixtures with low sand content (up to 20%). However, nothing prevents from contemplating them for supporting backfills. The purpose of using formulations with high sand content (from 50 to 80%) was to study supporting backfills.

The following conclusions result from the second series of laboratory tests:

- Since adding 10 to 20% of sand does not provide any significant increase in the dry density and in moduli, that solution was discarded;
- Adding 70% of sand allows for dry densities in the order of 2 t/m^3, which is a significant improvement in relation to pure argillite. Oedometric moduli are slightly improved, but results are disseminated. Moduli under small loading do not always meet the objective. The friction angle increases also and stabilizes at 29°. The behavior of the mixture remains dominated by the clay component. The behavior seems to shift around a 70%-sand concentration (small linearity loss of the punching curves). A formulation consisting of ⅓ argillite and ⅔ sand was selected for supporting backfills, which is a compromise ensuring a good resistance of the sloping backfill;
- Adding lime improves significantly the backfill modulus. However, the perennity of that improvement is not guaranteed. In addition, the dry density of the argillite/lime mixture's SPO is slightly behind that of reworked pure argillite. Consequently, it does not seem justified to select lime at the current study stage;

- The purpose of adding bentonite is to improve the swelling capability of the backfill. However, swelling tests did not show any significant improvement (for a limited addition of 2%). The other characteristics of the backfill are deteriorated by the addition of bentonite (reduction in the SPO dry density, increase of plasticity). Consequently, the addition of bentonite was discarded.

The selected objective for the demonstrator is a dry density corresponding to 95% SPO, both for pure argillite and for the argillite/sand mixture. The corresponding dry densities are as follows:

- 1.74 t/m^3 for pure argillite;
- 1.93 t/m^3 for a mixture of 33% argillite and 67% sand.

Saturation tests

Complementary laboratory tests were conducted on reworked pure argillite in order to understand better its behavior during saturation (subsidence/swelling) and to assess its deformability after saturation [4].

Those tests show that free swelling increases with the dry density of the samples (foreseeable result) and is more significant for the driest samples. Free swelling may reach approximately 10%.

In addition, the swelling pressure was reassessed. Depending on the experimental protocol, it varies between 25 and 500 kPa.

Lastly, tests have helped to compare moduli before and after imbibition. "Saturated" moduli lie much lower than "unsaturated moduli". Consequently, imbibition results in "erasing" a large fraction of the desaturation-induced rigidity.

Compaction mode and percussion rammer

Plate ramming was selected for compaction purposes [5]. A hydraulic hammer (Figure 2) is mounted on the arm of a power shovel and equipped with a metal plate. The percussion rate is adjustable and the form of the plate has the same curvature radius as the drift vault. A small plate and a small power shovel are used in order to allow the work to be carried out in the demonstrator.

Figure 2. Hydraulic percussion rammer mounted on a power shovel.

Due to the very high impact level and the relatively low rate being used (a few hundred strokes per minute), the technique is closer to percussion than vibration. That compaction mode is adapted to clay materials, since vibrations are considered of a poor efficiency for clays.

TEST PADS AND OTHER PRELIMINAIRY TESTS

The series of preliminary tests carried out in May-June 2005 helped to validate and to refine the compaction methods before applying them at full scale in the Demonstrator.

Tests on supporting wall (test pads)

Tests on the supporting wall (or "test pads") were used to check the compaction equipment under favorable conditions (in open air) and to record the first dry-density measurements *in situ*.

The material was spread in successive layers, ranging from 10 to 23 cm (after compaction) for pure argillite, and from 16 to 30 cm (after compaction) for the argillite/sand mixture. Tests also provided an opportunity to vary the compaction and percussion-rate times. Results were assessed by density measurements recorded by gamma densimeters. A few complementary controls were performed: Panda penetrometer, sample collection for laboratory tests, plate tests, etc. The overall dry-density objective (corresponding to the compaction energy of 95% SPO) was met. It was noted that the inclination of the layers did not pose a specific problem: the cohesion of the materials and the manageability of the plate would allow for vertical slopes to be contemplated.

The number of required compaction application to obtain the appropriate density is 2 t/m^3 for pure argillite and 3 for the argillite/sand mixture. In both cases, the use of higher rates is necessary (600-700 strokes per minute). Each compaction application lasts between 7 and 10 s.

Culvert tests

The culvert test is designed to test the rammer within a confined environment. A concrete culvert has the same geometry as the drift, but at a smaller scale. The interior section of the culvert is 2.06 m (height) by 3.04 m.

The thickness of the layers after compaction varies between 20 and 25 cm. The objective of achieving a dry density of 95% SPO was met.

A slaking of the backfill on the vault was detected a few days after it was installed. It reached 2 cm at the level of the vault and progressively reduced on the side wall. It probably resulted from an unusual hydric shrinkage in comparison to standard conditions in underground media (evaporation associated with strong sunshine).

DEMONSTRATOR: SIZING AND CONSTRUCTION OF THE CONCRETE STRUCTURE

The Demonstrator consists of a 20-m-long tube of reinforced concrete with a horseshoe-form section of approximately 10 m^2. The swelling efforts of the backfill likely to occur during the saturation phase, as well as the lateral-thrust efforts during the execution of an axial-thrust test lead to the following sizing for the demonstrator walls (Figure 3):

- Wall thickness: invert: 65 cm ; side wall: 50 cm ; vault: 40 cm
- Steel ratio: up to 240 kg/m^3 of concrete.

The size of the structure is designed to ensure an internal pressure of 0.9 MPa (see the description of the axial-thrust test further below).

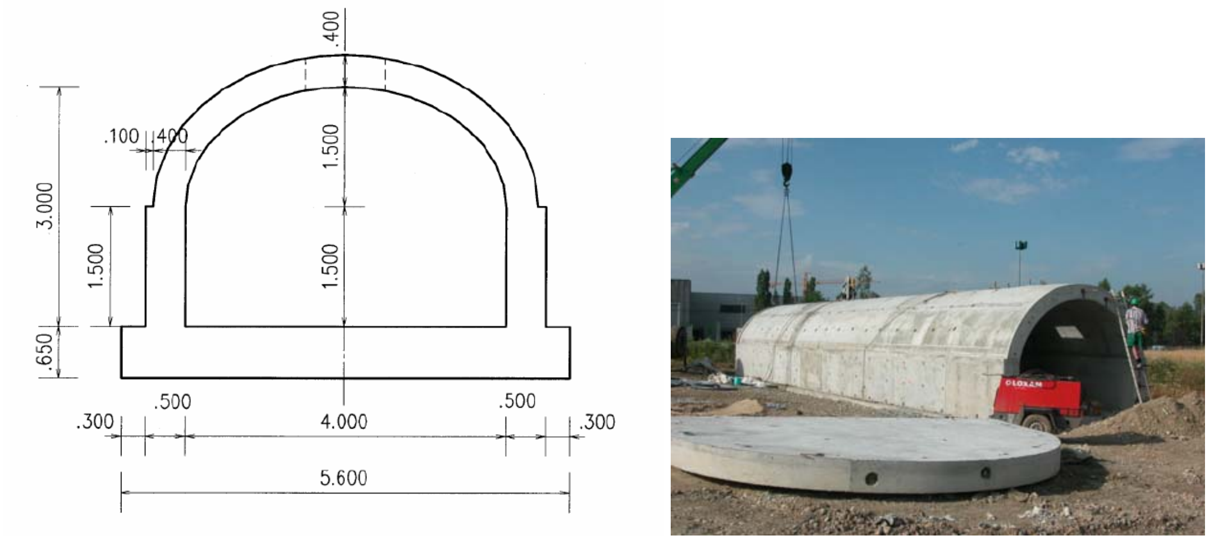

Figure 3. Dimensions of the Demonstrator and view of the Demonstrator during construction.

In addition, the Demonstrator is equipped with 11 longitudinal reentrants designed to accommodate ultimately pre-stressing wires for any potential axial-thrust test. Four large reentrants measuring 1 m by 1 m are fitted in the vault in order to perform plate tests from the outside of the Demonstrator. Other reentrants are intended for instrumentation cables and for 192 tapping points designed to ensure the saturation of the backfill after installation.

Two doors (or “closing shells”) made of reinforced concrete are used to shut the Demonstrator; the southern and northern doors are 20 and 30 cm thick, respectively. The thinnest door (southern) would be removed during any potential axial-thrust test.

BACKFILLING FOLLOW-UP, CLOSURE AND POST-CLOSURE CONTROLS

Preparation of backfill and backfilling

The backfill was prepared *in situ* and in a plant (weighed argillite/sand mixture). With due account of the material-storage conditions (in open air and in summer), it was necessary to humidify materials frequently before using them. In total, 4.5 and 3.2 m^3 were added to the argillite/sand mixture and to pure argillite, respectively.

Backfilling requires a material-supply phase in layers, followed by a compaction phase.

Supply is provided by buckets. A specific bucket has been developed in order to raise the material in layers under the demonstrator vault. Since it is impossible for the conventional tilting of the bucket to occur under the vault, a push-type hydraulic jack system was designed and manufactured.

A percussion rammer mounted on a mini caterpillar shovel, small enough to enter the Demonstrator and to conduct compaction operations up to a distance of 3.6 m in front of the caterpillars (Figure 2), was used for compaction purposes. The size of the plate is provided above (Figure 2).

In order to be accessible during a potential axial-thrust test, the argillite/sand mixture was installed first (it leans on the southern door, with the door shut before the beginning of the backfilling phase). The thickness of the layers before compaction varied between 35 and 40 cm between the first and last days. The transition to 40 cm helped to save time without deteriorating the compaction quality.

The average rate of the overall test is in the order of 4 m^3 per shift (compacted cubic meter)

Density and water-content measurements during installation

During backfilling, many controls were performed by using the tested methods for test pads. The objective in terms of dry density was met as follows [6]:

- In the argillite/sand mixture (supporting backfill), 218 measurements were recorded; dry density varied between 95 and 103% SPO (for an objective of 95%); the water content ranged from 9 to 12% (W_{SPO} = 11%);
- In pure argillites (standard backfill), 40 measurements were collected; dry density varies between 95 and 102% SPO (for an objective of 95%); the water content ranged from 13 to 16% (W_{SPO} = 14.2%);
- Even if heterogeneities were detected, no significant density decrease was noted close to the vault.

Closure of the Demonstrator

The sound cohesion of the compacted backfill helped to prepare a slightly protruding vertical face in relation to the extremity of the concrete structure. That face remained stable without any specific problem during the necessary time for the preparation and installation of the door (about one night and one morning). The door, equipped with its sealing ring, was installed and bolted.

Endoscopic recordings from the Demonstrator roof

One of the objectives was to limit the void to 3 cm under the vault. Endoscopic measurements were made through the reentrants in the Demonstrator roof and showed that the objective was met [6]. The void was millimetric in size during the first measurement (average: 0.6 mm; maximum: 2 mm) and had increased by 0.5 mm on average during the second measurement, two weeks later (no measurement has been made since).

Pressiometric tests carried out from the Demonstrator roof

Six surveys including three pressiometric tests each were carried out [6]. Within two boreholes, the tests were submitted to loading/unloading cycles[4].

Pressiometric tests are designed to calculate not only pressure limits and creep pressures, but also Ménard pressiometric moduli and cyclic pressiometric moduli.

Results do not seem to adjust themselves according to depth, which shows that compaction is as efficient at the vault level as at mid-height.

The Ménard pressiometric moduli characterize the first loading of the backfill (pseudo-elastic behavior). Those moduli vary between 4 and 13 MPa for the argillite/sand mixture and between 0.3 and 18 MPa for pure argillites. No explanation is provided for the broader dispersion of results in the case of pure argillites.

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4. According to the AFNOR P.94-110-L Standard.

Cyclic pressiometric moduli reflect the more clearly elastic behavior of the backfill. Those moduli are notoriously higher that the Ménard moduli (by an average factor of 5): they range from 22 to 39 MPa for the argillite/sand mixture and from 14 to 46 MPa for pure argillites. Once again, the results for pure argillites are more dispersed.

If we only focus on comparing the averages of cyclic moduli, we observe an increase in the order of 10% between the moduli for argillite/sand mixtures (30 MPa) and those for pure argillite (27 MPa).

Those values may be converted into Young's moduli on the base of a correlation formula. Young's moduli of 60 and 40 MPa are therefore obtained for the argillite/sand mixture and for pure argillite, respectively.

Plate-loading tests carried out from the Demonstrator roof

Four loading tests with a plate measuring 60 cm in diameter were conducted from the four reentrants in the Demonstrator roof [6]. Two types of loading were performed as follows:

- Cyclic tests under light loading (pressure under the plate in the order of 0.4 MPa) and therefore of small displacement (maximum displacement of 45 mm);

- Punching tests for which the displacement was pushed up to 20 cm (tests Nos. 1, 3 and 4), and even up to 50 cm (test No. 2).

Several moduli were calculated on the basis of the cyclic tests (Figure 4).

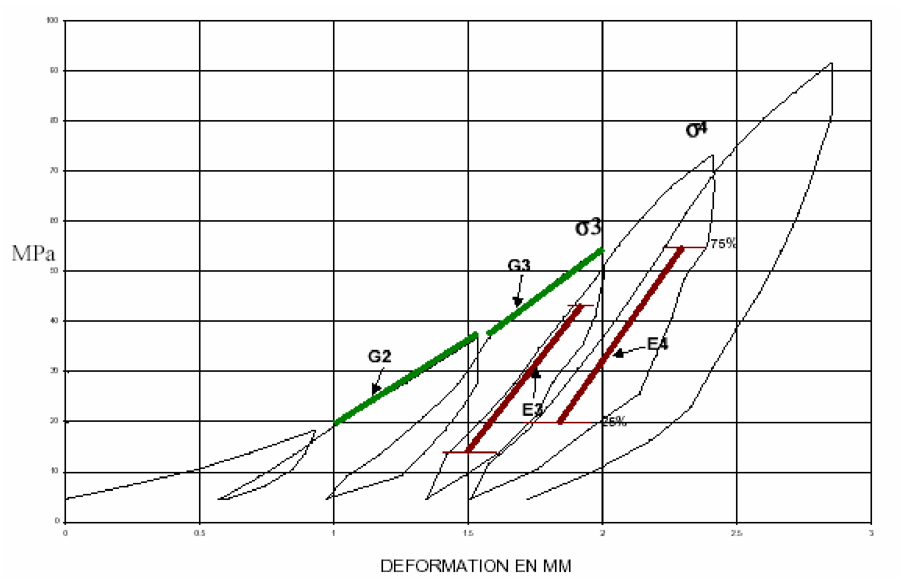

Figure 4. Plate tests: overall deformation module, *G*, and elastic deformation module, *E*.

The overall initial moduli vary between 3 and 17 MPa, and are approximately three times higher for argillite/sand mixtures than for pure argillite. The initial elastic moduli range from 28 to 81 MPa. Once again, the moduli for the argillite/sand mixture are much higher than those for pure argillite (average of 31 MPa).

During the cycles, the overall modulus tends to decrease (increase in plasticity), whereas the elastic modulus tends to increase (elastic rigidification). Elastic rigidification is higher for the argillite/sand mixture than for pure argillite.

LONG-TERM FOLLOW-UP PROGRAMME

Saturation device and long-term follow-up

The purpose of saturating the backfill is to assess the life-scale capability of the backfill to swell during imbibition. Saturation should also allow for axial-thrust test to be performed in order to measure saturated moduli.

Water is injected in the backfill through 192 "tapping points" distributed at a rate of one tap per square meter. The water pressure is limited to the pressure of the network (*i.e.,* approximately 2 bars). Various sensors are installed in the concrete (deformation[5] and temperature) and in the backfill itself (total stress, interstitial pressure, humidity and settlement) [7].

Water was supplied for the first time on September 27, 2005. Leaks appeared on both doors. Due to the significance of those leaks, the water supply was stopped temporarily. Various external interventions were required.

It is still too premature to draw any lessons from the recordings, because the instability of the saturation complicates any interpretation for the time being.

Possibility of conducting an axial-thrust test

The purpose of the axial-thrust test is to check the bearing of the supporting backfill on a large scale. Contrary to plate tests carried out from the Demonstrator roof, the axial-thrust test could be conducted in a full section, thus simulating the impact of the swelling-clay plug in a drift or in a shaft. In fact, plate tests involving punching do not pretend to be representative of the operating conditions of a supporting backfill submitted to a swelling-clay plug. In the case of a solicitation in a full section ("piston-like" mode), friction points will be mobilized between the backfill and the drift lining. Arch actions will occur and rigidify the backfill.

In order to reduce the thickness of the structure, the lateral thrust of the backfill was limited to 0.9 MPa, corresponding to an axial thrust of 1.35 MPa. Specifications for prestressing wires call for the use of 11 7T15S wires. The thickness of the northern door (30 cm) takes into account the axial-thrust test and may withstand a thrust of 0.18 MPa. However, the southern door (on the side of the argillite/sand mixture) is not sized in relation to the axial-thrust pressure, since it would be dismounted if the test is performed. The axial-thrust test could be carried out in 2009 on a partially-saturated backfill or later , if saturation took longer than expected.

PUTTING RESULTS IN PERSPECTIVE

For comparison purposes, the results achieved by SKB are presented here during experiments on drift backfills. The tests described below took place in Sweden and deal mostly with backfills in which muck was used. Since the Swedish project involves a granite formation, those backfills normally consist of 70% crushed granite as produced by a tunnel-boring machine. Adding swelling clay to it helps to reduce the permeability of the backfill (that function is now required by the Andra concept). That partial addition of clay also allows for the SKB-tested backfill to be reconciled to some extent to

5. As a complement to conventional extensometers with a vibrating wire, an optical-fiber extensometer was sunk in the concrete for testing purposes.

Andra backfills. Consequently, Swedish tests are primarily transposable to the supporting backfills of the Andra concept. However, a Swedish test was also carried out with pure argillite.

That short comparison emphasizes the sound results achieved on Andra's Demonstrator. The dry densities reached by the Demonstrator are located indeed within the upper range of the SKB values.

Lessons learnt from the "Buffer Mass Test" (BMT)

A "Buffer Mass Test" was carried out in 1980-85 at the Stripa Mine, in Sweden [8]. Among other things, its purpose was to check backfills of the drift. An unlined 30-m-long drift was backfilled with a mixture of swelling clay and sand.

In the lower section of the drift, a mixture consisting of 90% sand and 10% swelling clay was spread in layers ranging from 15 to 30 cm in thickness. A 400-kg vibrating plate was used for compaction purposes at a rate of 10 to 15 applications per layer.

The lack of space for the operation of the machinery close to the vault led to the use of a backfill-projection method in the upper areas. The proportion of swelling clay was raised to 20% in those areas in order to improve the swelling potential, thus compensating for the lowest dry densities due to projection. A wet method without compaction was used for projecting the backfill. The test involved also filling vertical cells with swelling-clay rings and by backfilling upper areas. The backfill was similar to that implemented in the lower section of the drift (10% swelling clay). That backfill was compacted in 10-cm layers with a hand pneumatic vibratory rammer.

The following dry densities were achieved in the drift: 1.25 t/m^3 under the vault and 1.77 t/m^3 in the lower section. The best dry density was reached in cells with a value of 1.81 t/m^3. The test showed that the differences in density were related to the implementation method being used.

Lessons learnt from the "Field test of tunnel backfilling"

A "Tunnel Backfilling Test" was performed in 1996 at the Aspö Underground Laboratory, in Sweden [9]. It consisted in setting in place various mixtures containing muck generated by tunnel-boring machines) and swelling clay. The specific proportion of swelling clay varied between 0 and 30%. Flat and inclined beds were created. Flat beds were compacted with a vibrating roller, and a small vibrating plate was used on the sides of the drift. Inclined beds were compacted with an especially-adapted vibrating plate.

The test helped to establish that the implementation of backfills in flat beds was feasible, provided that the worksite conditions are sufficiently dry. In the presence of significant amounts of water, swelling clay forms a gel that hinders compaction. That problem is smaller when backfilling with inclined beds.

The test also helped to recognize the zoning of densities in inclined beds; dry densities are higher in the core of the backfill, but low close to the border.

Lessons learnt from the "Backfill and Plug Test"

The installation of the backfill for the "Backfilling and Plug Test" was completed in 1999 at the Aspö Underground Laboratory [10]. Water saturation was reached by using permeable layers. Saturation started in 1999 and has been followed up ever since [11].

Two types of backfills were tested: (1) a backfill containing 70% of crushed granite and 30% swelling clay, and (2) a backfill of pure crushed rock, completed by blocks of swelling clay and pellets spread over the vault.

A vibrating plate was used to compact the layers, with a final thickness of about 20 cm after compaction.

As more and more experience was gained during the test, dry densities kept improving. Improvements were particularly noticeable in the closest zones to the drift vault. However, compaction in those zones was disturbed by the presence of many sensors and instrumentation cables. In the central section, the average dry density reached 1.7 t/m^3 against 1.5 t/m^3 in peripheral sections. Nonetheless, the thickness of that zone with a lower density is limited to a few decimeters. The overall dry density is estimated to be above 1.65 t/m^3.

The resaturation timescale depends heavily on the applied water pressure. According to calculations, five years are expected for a water pressure of 100 kPa, compared to one or two years for it to reach 500 kPa. The latter value was selected for the test. Stages of 100 kPa were applied between October 2001 and January 2002. The effect of resaturation is visible on the suction curves. The backfill was almost fully resaturated by the end of 2002.

Lessons learnt from the "Prototype Repository Test"

The "Prototype Repository Test", carried out at Aspö Underground Laboratory included various aspects relating to the implementation and closure of a repository. Plans call for the test to be followed up over a 10-year period. The test involves backfilling a drift [12].

Backfilling consisted in setting in place 20-cm-thick layers after compaction, inclined at 35°. The composition of the backfill was consistent with most of the tests carried out by SKB (*i.e.,* 30% swelling clay and 70% ground rock). An abundant instrumentation was also installed.

The dry densities achieved were in the order of 1.7 t/m^3, and once again, with gradual improvements; the first layers had a dry density in the order of 1.5 t/m^3, whereas the last layers headed closer to 1.8 t/m^3.

Lessons learnt from the tests carried out with Friedland clay

SKB investigated the possibility of backfilling repository drifts with a natural clay called "Friedland clay", which is relatively rich in smectites, thus conferring it the swelling capability being sought.

In the framework of the SKB concept, the required dry density for a Friedland-clay backfill was estimated to 1.5 t/m^3. Such a density is easily reached on the samples of the Proctor test. The purpose of the *in-situ* test was to check what density could be achieved with the compaction equipment developed for the crushed rock / clay mixtures under full-scale conditions. The test was carried out at the Aspö Underground Laboratory [13].

Layers with 30 cm in thickness were compacted. The dust generated during that operation is very sensitive to the water content of the material. A water content higher than 10% is considered necessary. The first clay batch to be delivered had a water content ranging only from 5 to 7 %. Due to the presence of dust, compaction operations had to be limited to 3 s for each position of the vibrating plate. The end result was dry densities in the order of 1.4 t/m^3 to 1.475 t/m^3, which were below specifications.

A new test was carried out with a water content of 12.9%, where dust conditions were excellent. However, dry densities after compaction dropped to about 1.3 t/m^3. The required compaction energy is therefore higher in the case of the new water content (that result is not transposable to the argillite-based backfills of the Meuse/Haute-Marne Site for which the optimal water content lies between 13 and 14%). The test shows the unsuitability of the vibrating plate for Friedland clays. In general, vibrations are not considered as an appropriate mode for compacting clay materials. Static or percussion compaction is more adapted.

CONCLUSION

The objectives of the Demonstrator were met: an implementation method was tested satisfactorily. The technique used, involving a small percussion plate, provided satisfactory results in terms of dry densities that are above the 95%-SPO objective. Although heterogeneities were detected, no significant decrease in density was recorded close to the vault. The stability of the face helped to install the backfill in vertical slopes with 3 m in height, even for the argillite/sand mixture. Deformation moduli were measured by pressiometric or by plate-loading tests: they are relatively low and reflect the plastification of the backfill due to the loading mode. Elastic moduli (Young's moduli), which are also resulting from the pressiometric and plate tests, are clearly much higher. Those moduli are satisfactory. In accordance with forecasts, values are higher for the argillite/sand mixture than for pure argillite.

The Demonstrator is now in its long-term follow-up phase. Sensors and a water-saturation system were installed. Some leaks have delayed priming operations. An axial-thrust test is contemplated, but will only be performed if the saturation level of the backfill is considered sufficient.

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