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LUCOEX

# (GRANT AGREEMENT: 269905)

## DELIVERABLE (D-N°:D2.5)
## Emplacement Report LUCOEX – WP2

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# Summary

The Full-Scale Emplacement (FE) Experiment at the Mont Terri Rock Laboratory is a full-scale heater test in a clay-rich formation. The emplacement task of this project is part of Nagra's participation in the EC co-funded "Large Underground COncept Experiments" (LUCOEX). It refers to the current Swiss reference repository concept for spent fuel / high-level radioactive waste (SF/HLW) and demonstrates the feasibility of waste emplacement and backfilling of emplacement tunnels.

Based on experience from preceding projects and on extensive pre-testing, a prototype backfilling machine with five horizontal screw conveyors was designed and manufactured. This prototype machine was extensively tested in a surface industrial facility before putting it into operation at Mont Terri. A mock-up test was conducted in order to check and optimise the technology in a setup that was representative for the conditions at Mont Terri. Process-related interfaces such as the geometries of other components (bentonite pedestal and heater, sensors and cables etc.), as well as a work programme for Mont Terri, were also investigated. Moreover, quality control (QC) of the backfill offered a variety of new options regarding the requirements from a long-term safety perspective (i.e. buffer density and homogeneity) that are not conceivable in an underground facility. Besides conventional density assessment by mass-volume-balance, this included different methods for local density assessment with dielectric tools, gamma-gamma-logging, cone penetration testing, as well as the possibility of implementing longitudinal viewing windows in the dummy tunnel liner. The local dry density values derived from these methods range from 1.4 to 1.7 t/m$^3$. Generally, they exhibit good consistency.

Apart from these local density assessment measures, repeated geodetic laser scans of the proceeding slopes at different positions yielded distinct volumes and hence sectional values for dry density calculated from mass-volume balance. The average dry density in the mock-up test was between 1.48 and 1.55 t/m$^3$. In the FE emplacement tunnel at Mont Terri, the overall dry density was 1.489 ± 0.003 t/m$^3$. The target value (1.45 t/m$^3$) was clearly met in both the mock-up test runs as well as in the FE emplacement tunnel at the Mont Terri URL.

All backfilling operations at Mont Terri and at the pre-testing sites were achieved without any accidents or serious breakdowns.

However, the conveyor screws showed significant signs of wear. Future developments should address this issue. Also, further quality improvement in horizontal buffer/backfill emplacement is conceivable, together with advances in local density assessment.

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# Glossary

| Term | Meaning |
|---|---|
| FE Experiment | Full-Scale Emplacement Experiment |
| GBM | (Highly compacted) granulated bentonite mixture |
| Heater | Test container with heater unit |
| LUCOEX | Large Underground COncept EXperiments |
| Mock-up test | Test of the backfilling machine in a 1:1-scale tunnel model |
| Nagra | National Cooperative for the Disposal of Radioactive Waste |
| SF/HLW | Spent fuel / high-level waste |
| URL | Underground Rock Laboratory |

# 1 Introduction

The emplacement part of the Full-Scale Emplacement (FE) Experiment refers to the current Swiss reference repository concept for spent fuel / high-level radioactive waste (SF/HLW) (Fig. 1). It is based on a multibarrier system. Besides the natural geological barrier (Opalinus Clay), it comprises several engineered barriers, such as the disposal canister, the backfill surrounding the canister and several tunnel seals (Figure 1).

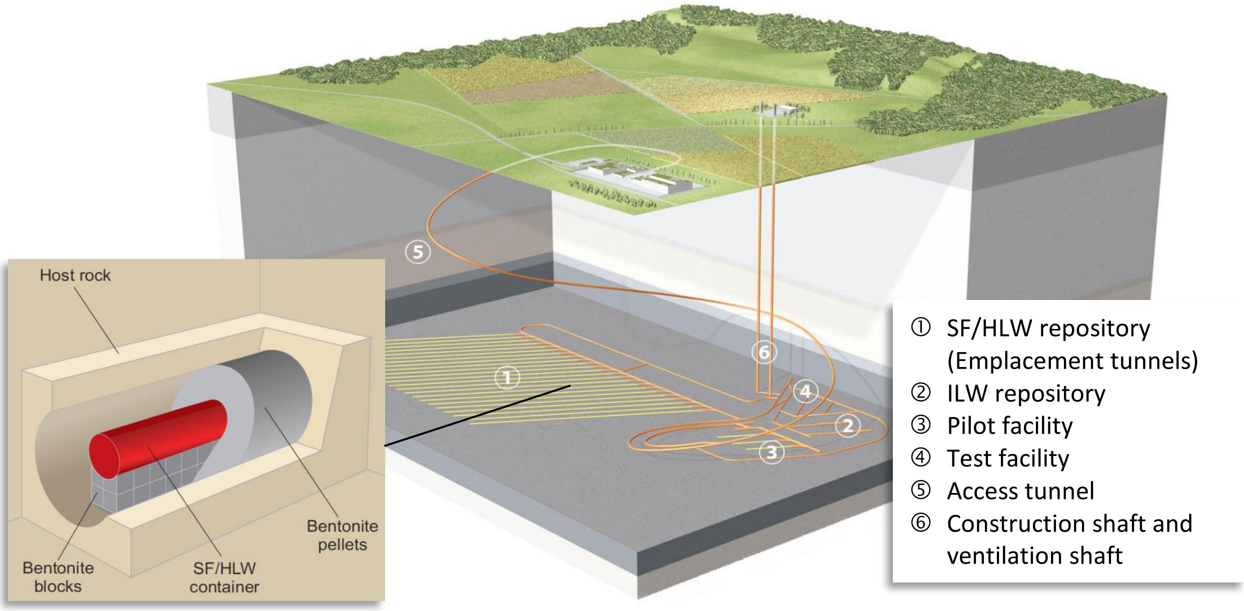


Figure 1: Swiss reference repository concept for spent fuel / high-level waste (SF/HLW)

The SF/HLW canisters will be emplaced in disposal tunnels (inner diameter of ca. 2.5 m). The disposal canisters will be embedded in a suitable buffer material made of bentonite blocks and (highly compacted) granulated bentonite mixture (GBM). The respective tunnel section will be backfilled with GBM after emplacement of each disposal canister.

The FE Experiment at the Mont Terri Rock Laboratory is a full-scale heater test in a clay-rich formation. It aims at investigating the effects of the heat-producing waste on the coupled thermal, hydraulic and mechanical ("THM") long-term behaviour of the surrounding rock. It also demonstrates the feasibility of tunnel construction, waste emplacement and backfilling of a spent fuel (SF) / vitrified high-level waste (HLW) repository tunnel. These feasibility-related topics represent Nagra's participation in the EC co-funded "Large Underground COncept Experiments" (LUCOEX) project.

The construction of the FE tunnel is described in Daneluzzi et al. (2014). Garitte et al. (2015) describe the requirements, manufacturing and QC of the buffer components. A new transportation and lifting vehicle was developed and manufactured for the emplacement of the heater elements (Jenni & Köhler 2015).

Based on the experience from the Engineered Barrier (EB) experiment (Kennedy & Plötze 2003) and the ESDRED project (Plötze & Weber 2007), a new prototype backfilling machine with five horizontal screw conveyors was developed, manufactured and extensively tested for the FE Experiment (Jenni & Köhler 2015) (Figure 2).

This prototype was used to backfill the horizontal FE tunnel with a diameter of 2.5 – 3 m with GBM. According to the requirements derived from the reference concept, this material had to be backfilled with an overall bulk dry density of at least 1.45 kg/m$^3$.

This report addresses the emplacement and backfilling part of the FE Experiment at Mont Terri.

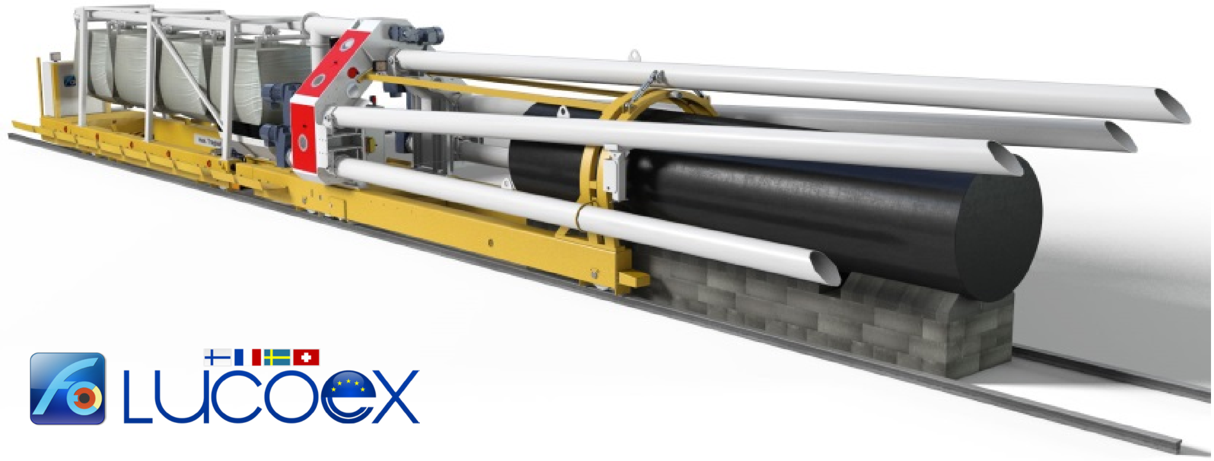


Figure 2: Prototype backfilling machine fabricated for the Full-Scale Emplacement (FE) Experiment.

Side note: The pictured feeding device containing bigbags does not exhibit any prototype character.

# 2 Backfilling of granulated bentonite mixture

## 2.1 Requirements

In line with the Swiss reference emplacement concept (Nagra 2002), a bentonite buffer material had to be emplaced around the three heaters in the FE tunnel at Mont Terri. The buffer emplacement concept for SF/HLW foresees the use of granular bentonite material as a backfill around the disposal canisters.

The final saturated density is considered to be the key property for ensuring adequate long-term performance of the bentonite-based backfill material in a repository since it directly influences the safety-relevant attributes such as swelling pressure, gas and water permeability, porosity and suppression of microbial activity. Suppression of microbial activity sets perhaps the most stringent density requirement. Stroes-Gascoyne (2011) reported that microbial activity is clearly suppressed in highly compacted bentonite. Leupin & Johnson (2013) concluded that a saturated density of 1.90 $t/m^3$ (corresponding to a dry density of 1.45 $t/m^3$) is a desirable target as it will decrease the likelihood of microbially induced corrosion.

Hence, the major requirements regarding backfilling are attributed to the completeness of the backfilling around, before and behind each disposal canister allowing for:

- A target dry density of 1.45 $t/m^3$ or higher for the entire bentonite backfill. This includes the need for a high content of swelling minerals (i.e. basically montmorillonite) and
- A fairly homogeneous distribution of the backfilled GBM and the target dry density.

In selecting an appropriate backfilling method, the following aspects also had to be considered:

- Continuous backfilling process in a retreating mode for each disposal canister with high reliability and availability
- Iteration with the emplacement of disposal canister units incorporating pedestals made of highly compacted bentonite blocks
- Accurate backfilling quality for a varying tunnel radius due to gallery excavation deviations and support elements (e.g. shotcrete lining, steel ribs, etc.).

## 2.2 State of the art

In the past, Nagra has invested considerable effort in evaluating and improving feasible backfilling methods. The first tests on the production of granular bentonite with high bulk density were performed successfully by Naundorf & Wollenberg (1992). Borehole filling experiments were carried out from 1994 to 1996, where emplacement dry densities in the order of 1.4 to 1.5 $g/cm^3$ were achieved with the use of a pneumatic method and high density granular backfill materials made of MX-80 bentonite (Blümling & Adams 2008). The early testing of the pneumatic method provided a benchmark for the backfilling results. However, it was obvious that the boundary conditions would be very different with horizontal backfilling, especially regarding the flow behaviour of the bulk material (Kennedy & Plötze 2003).

Regarding horizontal backfilling of emplacement tunnels, a series of projects can be mentioned, starting several years after the borehole filling tests:

- The "Engineered Barriers" project (EB) (Kennedy & Plötze 2003, Kennedy 2003, Mayor et al. 2005); an important outcome of this project was the conclusion that the screw conveyance technique was the most promising one compared with other conceivable methods such as pneumatic or belt conveyance and combined approaches

- The "Engineering Studies and Demonstration of Repository Designs" project (ESDRED) (Plötze & Weber 2007) aimed at improving screw conveyance techniques as well as the granular buffer composition
- The "Heater E" experiment (HE-E) within the framework of the "Long Term Performance of Engineered Barrier Systems" project (PEBS) (Gaus 2011), addressing the thermal effects on the buffer material and the near-field in the host rock (half-scale experiment)

Further experience with backfilling horizontal tunnel sections (without waste containers) was gained in projects carried out by European partner organisations, such as:

- The "Prototype repository" project within the framework of the European Atomic Energy Community's R&T Specific Programme "Nuclear Energy, Key Action: Nuclear Fission Safety 1998-2002, area: Safety of the Fuel Cycle" (Andersson et al. 2005)
- The "Full Scale Sealing" (FSS) experiment within the framework of the "Demonstration of plugs and seals" (DOPAS) EURATOM FP7 technical project

Referring to the experience mentioned above, the screw conveyance technique is largely considered to be the most suitable method for granular bentonite backfilling with the desired quality, compared with other methods such as pneumatic, tube drag conveyance, slinger stowing, belt conveyance methods and manual backfilling.

## 2.3 Backfilling machine design parameter evaluation (pre-test A)

After basic discussions and decisions about a backfilling concept based on the screw conveyance principle, a first pre-test "A" was carried out in late summer 2012 (Figure 3). This pre-test aimed at:

- Investigating the potential for pushing the bulk material upwards in a concrete tube of 1.25 m diameter
- Examining the corresponding actuation parameters of the conveyor screw in order to design the backfilling machine for the FE Experiment.

For this task, one of the old screw conveyors that had been used for Nagra's ESDRED experiments was equipped with a frequency converter and a control display showing the actuation parameters such as rotation frequency, current consumption and engine torque.

Furthermore, the horizontal backfilling pressure resulting from the stuffing screw conveyor was measured by attaching a crane scale to the wire rope holding the machine. This information was useful for designing the brakes of the backfilling machine.

The maximum filling height was 2.05 m above ground in the centre of the concrete tube. This corresponds to a push-up height of approximately 70 cm above the horizontally aligned middle axis of the screw conveyor. The resulting horizontal force pushing the machine back was up to 9.5 kN with a short-term maximum power of 5.37 kW. However, at a normal power of around 3 kW, the reaction force held by the wire rope was between 5 and 6 kN.

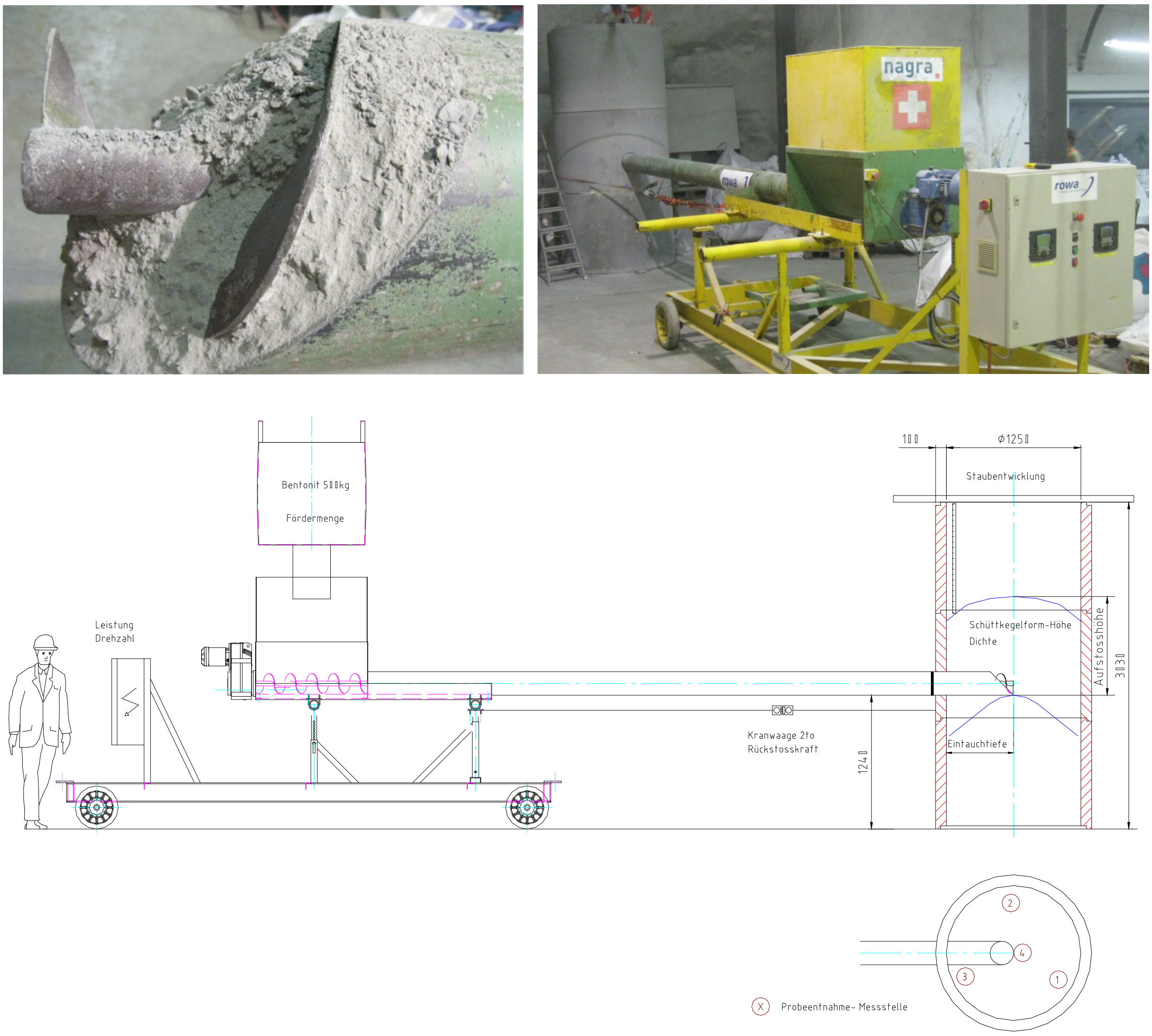


Figure 3: Conceptual sketch of pre-test A

## 2.4 Methodology optimisation (pre-test B)

As a consequence of open questions relating to local backfill quality due to segregation effects that had been discussed over the past years, the main aim of the second pre-test "B" was to visualise the backfill through a glass window.

Apart from this, the test series helped to optimise the granular bentonite material in terms of granulometric mixture. Various measures were also applied to evaluate the potential for mitigating segregation effects and increasing the backfill density. A promising result was observed with a flexible slope coverage that seemed to effectively reduce the segregation, as shown in Figure 4.

Density was mainly evaluated with the weight of the backfilled bentonite divided by a rough estimation of the volume. Besides the overall mass-volume density assessment, a novel approach to local density estimation was tested using a dielectric profile probe which could be inserted into pre-installed access tubes from the surface. This yielded density profiles as shown in Figure 5. These profiles show a uniform trend: while maximum density is consistently displayed at the position where the screw conveyor is directly stuffing the material, it generally decreases towards the bottom of the test box. The average dry density estimated with the dielectric tool was in good agreement with the overall dry density calculated from the mass-volume balance.


Figure 4: Visualisation of segregation effects depending on various measures during backfilling. Top pictures: $\rho_d \approx 1.43$ t/m$^3$ and no countermeasures. Lower pictures: $\rho_d \approx 1.46$ t/m$^3$, flexible slope coverage and broader grain size distribution

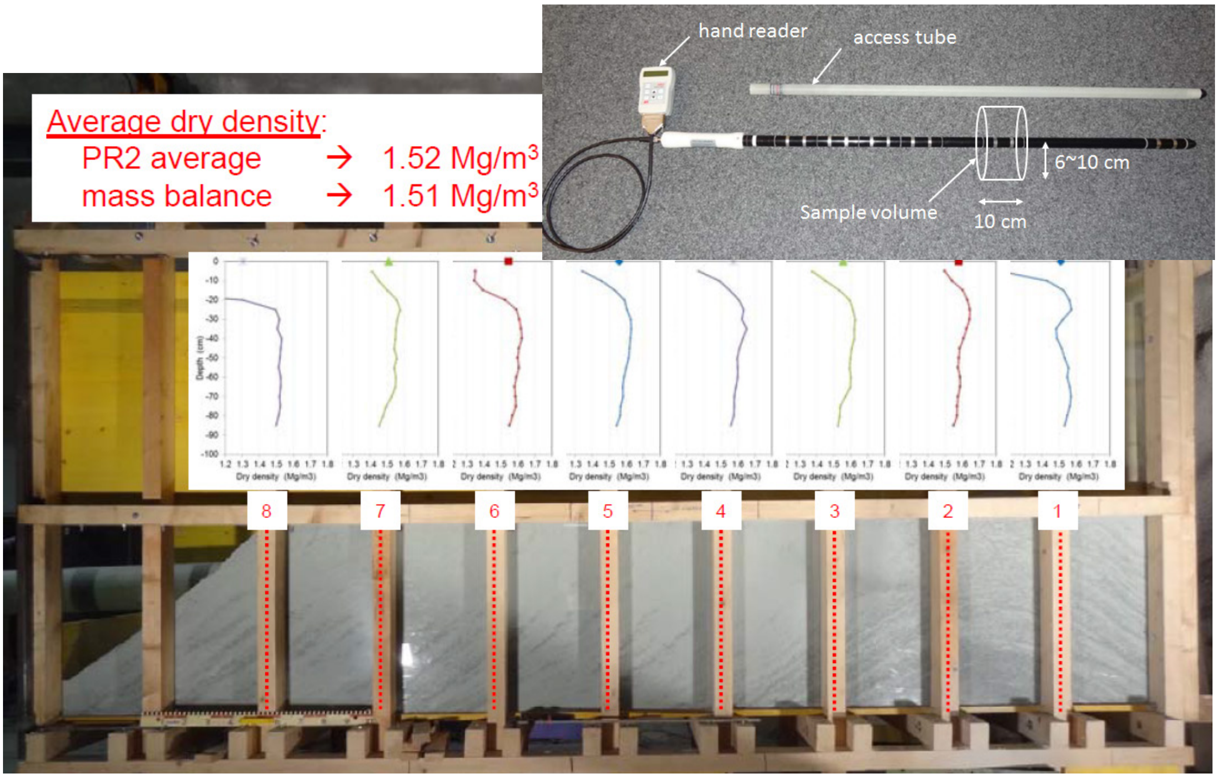


Figure 5: Local dry density estimation with dielectric profile probe PR2 (Delta-T Devices Ltd. UK).

Several approaches to increasing the backfill density were investigated: various slope coverages, local vibration (concrete vibrators) as well as sonic impacts by application of a ship's fog horn. Only slight improvements could be achieved, with dry densities in the range of 1.40 and 1.55 t/m$^3$. However, it should be pointed out that the material mixtures were also changed during the test series. From the small number of filling tests with distinct changes in one boundary condition each time, it was not clear if the results represented a trend or if they were within the statistical error and the range of measurement inaccuracy.

## 2.5 Prototype backfilling machine

On the basis of the pre-tests, the backfilling machine for the FE Experiment was designed in detail. The main components are shown in Figure 6. The backfilling machine was constructed between December 2013 and April 2014 by Rowa Tunnelling Logistics GmbH, Switzerland. It basically consists of a feeding unit loaded with bigbags containing the backfill material and the backfilling unit (Figure 6). For details about the design and manufacturing of the backfilling machine, reference should be made to Jenni & Köhler (2015).

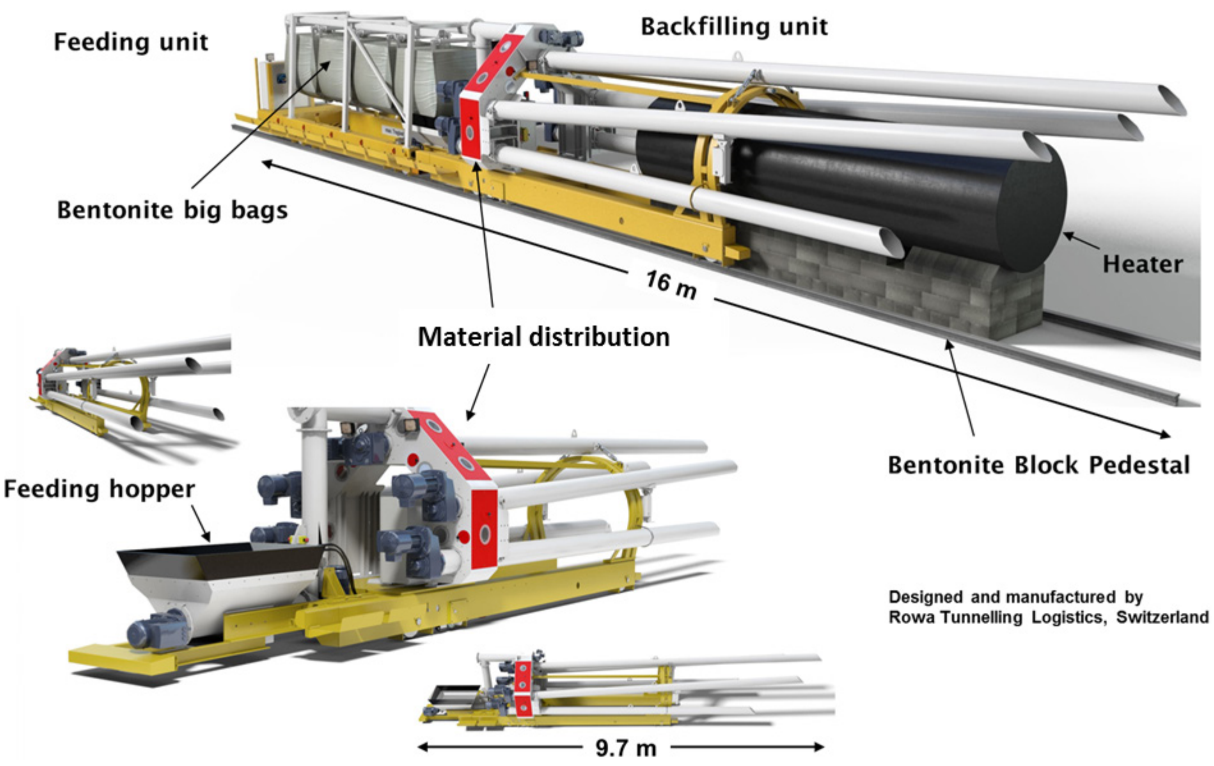


Figure 6: The backfilling machine for the FE Experiment.

## 2.6 Bentonite-based backfilling materials

For the FE Experiment, 70 tons of bentonite blocks (delivered in March 2014 by Laviosa MPC, France) and 346 tons of granulated bentonite mixture (GBM, delivered from December 2013 to January 2014 and May to June 2014 by CEBO Holland and J. Rettenmaier & Söhne, Germany) were produced with a natural sodium bentonite (Garitte et al. 2015). FE bentonite blocks (Figure 7, left), produced with Bentosund WH2 (formerly: Gelclay WH2) as a raw material are characterised by an average dry density of 1.78 g/cm$^3$. The associated strength of the blocks satisfies the structural strength require-ments for the pedestals and the bentonite block wall. The achieved dry density is a result of the adjustment of the water content of the raw material and of the compaction pressure to produce bentonite blocks that are as stable as possible with respect to changing climatic conditions. A higher dry density is possible, but with a resulting loss of resistance to climatic conditions. A lower dry density is probably feasible (increasing the water content), but this was not tested. The achieved block dry density value is relatively low when compared to other block productions, but a higher dry density is not considered favourable with regard to the required climatic and mechanical stability as well as the expected equilibrium of rock and swelling pressure level after future resaturation of the entire buffer.

The GBM (Figure 7, right) was produced in a four-step procedure (raw material, drying, pelletisation and mixing). The raw bentonite used for the GBM is National ® Standard WP2. Two distinct production runs were performed to deliver material for the pre-tests (production 1) and for the backfilling of the FE tunnel (production 2). The mixture quality was optimised during the productions, resulting in slightly different mixtures. Their main characteristics are described in Table 1. Mixture 1 was used in machinery calibration pre-tests (screw conveyor system function tests, glass wall tests at VSH, etc.) and was never emplaced in the FE tunnel or in the mock-up test. Mixture 2 was packed in pink bigbags and was used later in the mock-up test, for backfilling of the ISS section and the last tunnel part close to the retaining wall. Mixture 3 was packed in blue bigbags and was used later for the second mock-up test in Grono and to backfill the heated section of the FE tunnel. 5 tons of this mixture were conserved and will be used as reserve material and for performing further laboratory testing. Mixture 4 was packed in green and red bigbags and was not used in the FE experiment. Further details on the production are available in Garitte et al. (2015). Note that pouring dry density values are dependent on the measurement method. Hence, the values indicated here have no absolute character. Nevertheless, the 4 values were obtained with a standardised device and can thus be compared with one another.

Figure 7: Top layer bentonite blocks (left) and GBM (right) produced for the FE Experiment.

Table 1: Main characteristics of the FE GB mixtures.

| | Production | | Amount [t] | Colour code | Average standardised pouring dry density [g/cm$^3$] | Pellet dry density [g/cm$^3$] | Water content [%] | Fuller |
|---|---|---|---|---|---|---|---|---|
| Mixture 1 | 1 | Dec. 2013 – Jan. 2014 | 24 | - | 1.43 | 2.18 | 4 – 6 | Slight deviation |
| Mixture 2 | | | 106 | pink | 1.41 | 2.18 | 4 – 6 | Fines shortage |
| Mixture 3 | 2 | May – June 2014 | 184 | blue | 1.44 | 2.14 | 4 – 6 | Target |
| Mixture 4 | | | 32 | green, red | 1.39 | 1.95 | 7 – 9 | Target |

# 3 Mock-up test

## 3.1 Aims of the mock-up test

Before commissioning of the new backfilling machine at Mont Terri, extensive testing was necessary. A mock-up test in a surface industrial facility was carried with the following objectives:

1. Technology demonstration of the backfilling process with the backfilling machine
   a. Check and optimise the functionality of the entire "backfilling technology" system under realistic conditions
   b. Check and optimise the control parameters of the backfilling technology including calibration of the braking forces
   c. Check and optimise process-related interfaces such as the bentonite pedestal as well as sensor and cable positions for instrumentation, heater elements, etc.
2. Check the process sequences including their duration for the assessment of a work programme for the implementation at Mont Terri
3. Quality control (QC) of the backfill: global and local assessment of the bulk dry density backfilled into a dummy tunnel

Points 1 and 2 were addressed with priority in a first test run in May 2014. A second test run was carried out in August 2014 focusing on point 3.

## 3.2 Test set-up

An 8 m long dummy tunnel was constructed from standard 6 mm thick steel sheets that are widely available in the metal working industry. Rails with an inclination of 1% were installed on the concrete floor and in the dummy steel tunnel in line with the situation at Mont Terri. A dummy canister and a steel plinth representing the shape of the bentonite pedestal were also installed. Figure 8 to Figure 13 give an impression of the mock-up test setup and the backfilling operation.

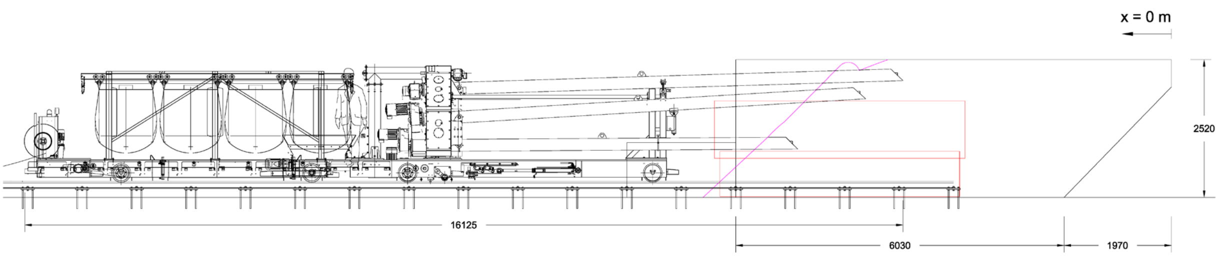


Figure 8: Conceptual sketch of the mock-up backfilling test.


Figure 9: Photo of the rear end of the backfilling machine ready to start backfilling the steel tunnel tube.


Figure 10: Photo of the backfilling machine in operation at the beginning of the mock-up test.

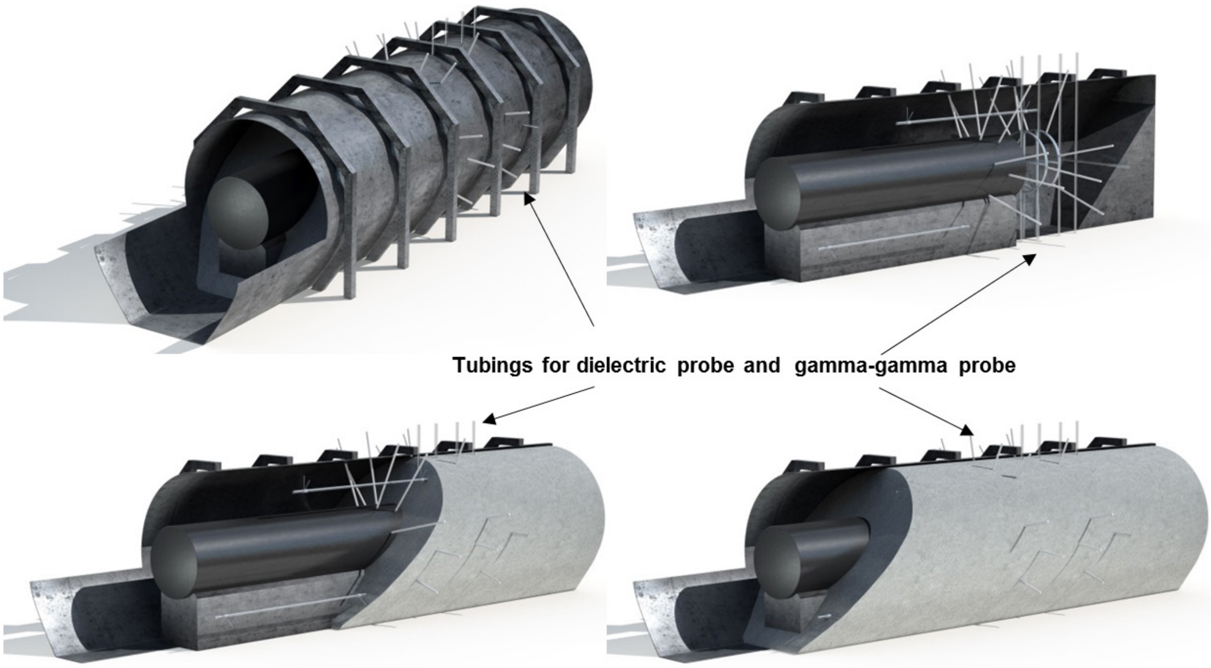


Figure 11: Mock-up tunnel rig with installed access tubes for local density profile estimations.

For the assessment of the distinct backfill density beyond the canister and around it by mass-volume calculation, the backfilling process was stopped at approximately half way in order to allow the slope to be accessed for geodetic laser scanning for exact volume calculation.

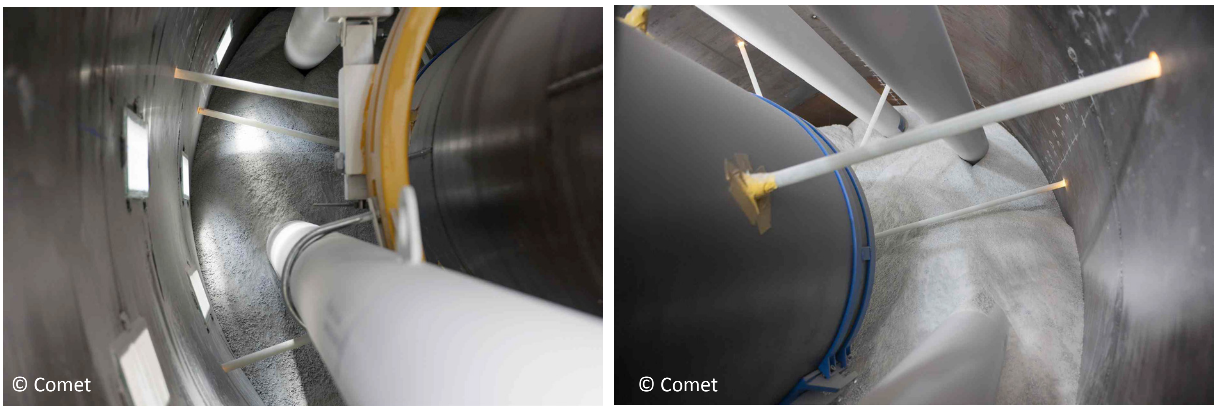


Figure 12: Photo impressions of the backfill slope from the first backfilling mock-up test approaching PR2 access tubes (May 2014).

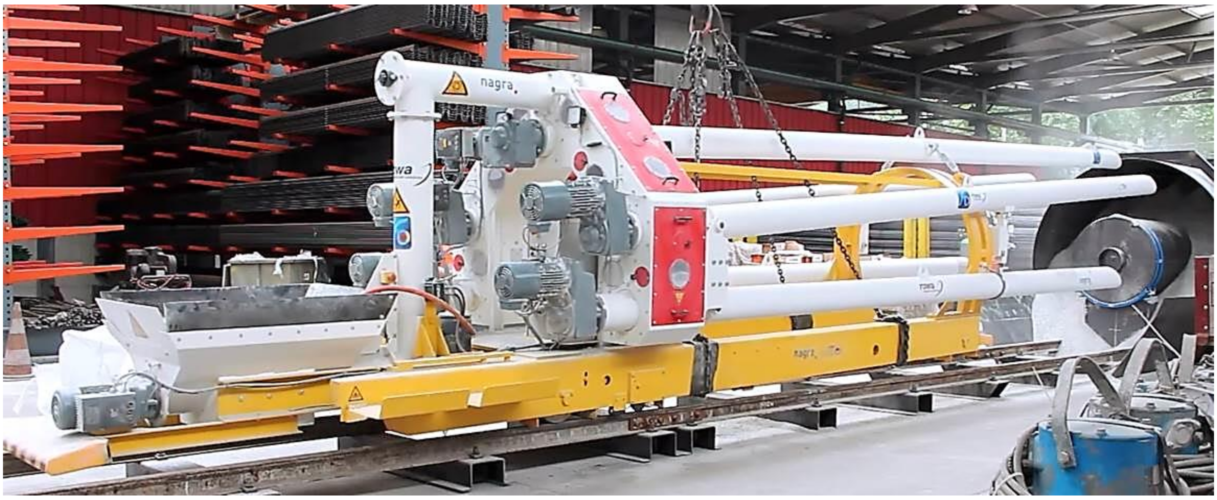

Figure 13: Photo of the backfilling unit being lifted off the rails with an overhead crane after completion of the backfilling.

## 3.3 Quality control

### 3.3.1 Density measurement methods

Since buffer density is the most important requirement from the long-term safety analysis perspective, QC focused particularly on this issue.

The conventional method for density assessment is the mass-volume balance, which yields reliable results for the overall (average) density of the bulk considered. For a record of the backfilled mass, every bigbag was weighed on a pallet truck incorporating a weighing unit with ± 2 kg accuracy. Dead weight such as pallets, empty bigbags and material samples were subtracted from the recorded weight.

Laser scanning was carried out by Flotron AG, Switzerland, in order to assess the shape of the backfill slopes. Knowing the geometry of the test tunnel tube and the position of the slope, the backfilled volume could be calculated. The mass-volume ratio then yields the density (for details see section 4.3).

For mock-up test filling No. 1 (May 2014, mixture 2, see section 2.6), only the overall density was calculated. In order to assess the backfilled density around the dummy canister separately from the density beyond it, two slopes were scanned in mock-up test filling No. 2 (August 2014, mixture 3, see section 2.6) (Figure 14). For the first scan (red in Figure 14), the backfilling process was stopped and the backfilling machine driven out of the tunnel. The second one (green in Figure 14) gives the overall backfilled volume.

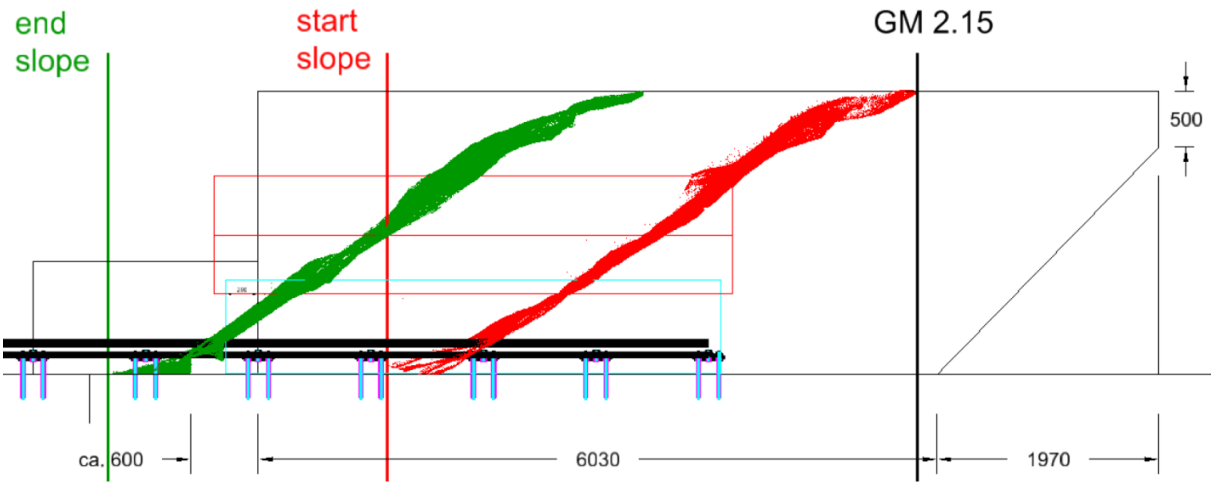


Figure 14: Slope scans for distinct volume estimation around the dummy canister and beyond it.

In addition to the average density assessment, local density profiles were estimated as follows

- Gamma-gamma logging (BLM GmbH, Germany) (Figure 15) in 4 vertical and 3 horizontal "PICO" tubes yielded 7 different density profiles after the second filling in August 2014
- Horizontal cone penetration testing (CPT, implemented by Geoprofile GmbH, Switzerland) (Figure 16); 9 CPTs were carried out after the first filling in May 2014, 10 CPTs after the second filling in August 2014
- Radial dielectric profile measurement with a "PR2" profile probe (Delta-T Devices Ltd. UK); 22 "PR2" access tubes were installed radially in holes through the dummy tunnel's steel liner towards the centre for this method (Figures 17 to 20).

Figure 15: Vertical gamma-gamma logging with operations on a scaffold around the test tunnel tube.

Figure 16: Horizontal cone penetration testing (CPT) after completion of the backfilling.

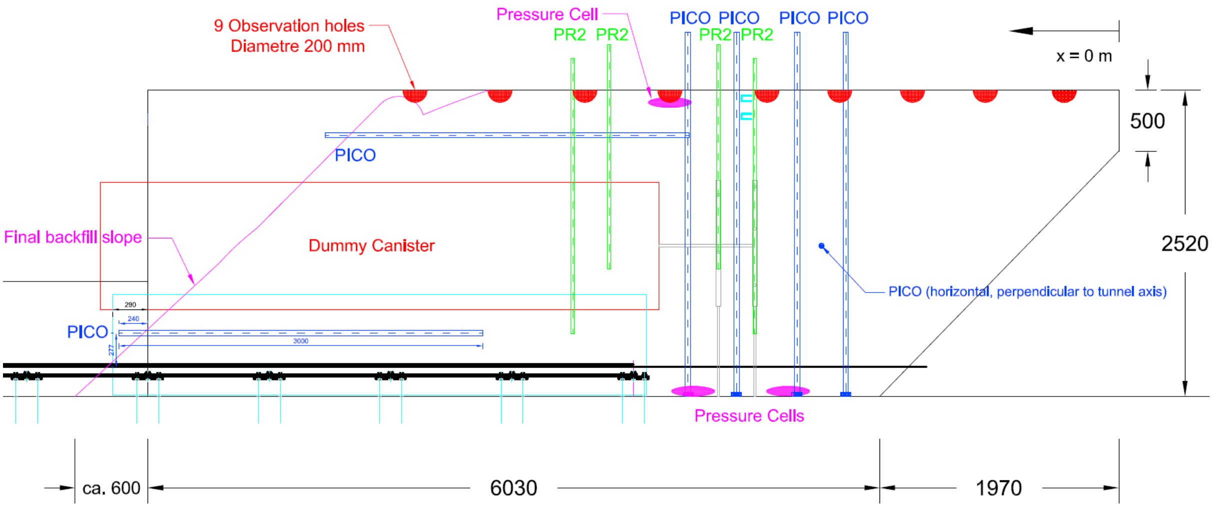


Figure 17: Longitudinal section of the test tunnel rig with installations for local density estimation.

Blue: Access tubes for "PICO TDR" profile probe (IMKO GmbH Germany) for gamma logging tool insertion

Green: Access tubes for "PR2" profile probe (Delta-T Devices Ltd. UK) insertion

Pink: Total pressure sensors

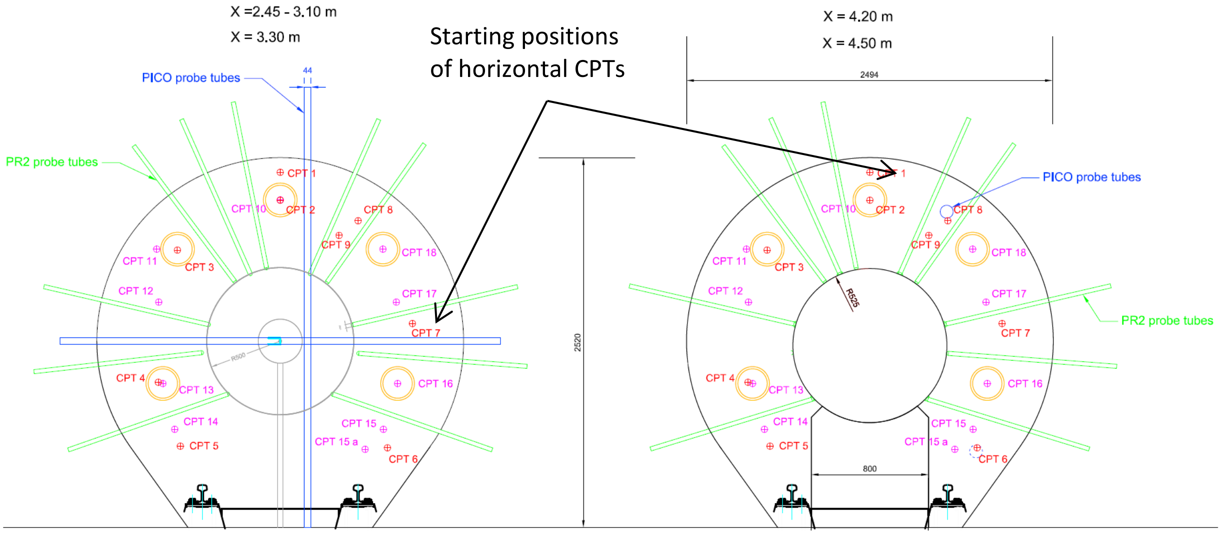


Figure 18: Cross-section of the test tunnel rig with installations for local density estimation and starting positions of horizontal CPT profile measurements (red: profiles taken after the first backfilling in May 2014; pink: profiles taken after the second backfilling in August 2014).

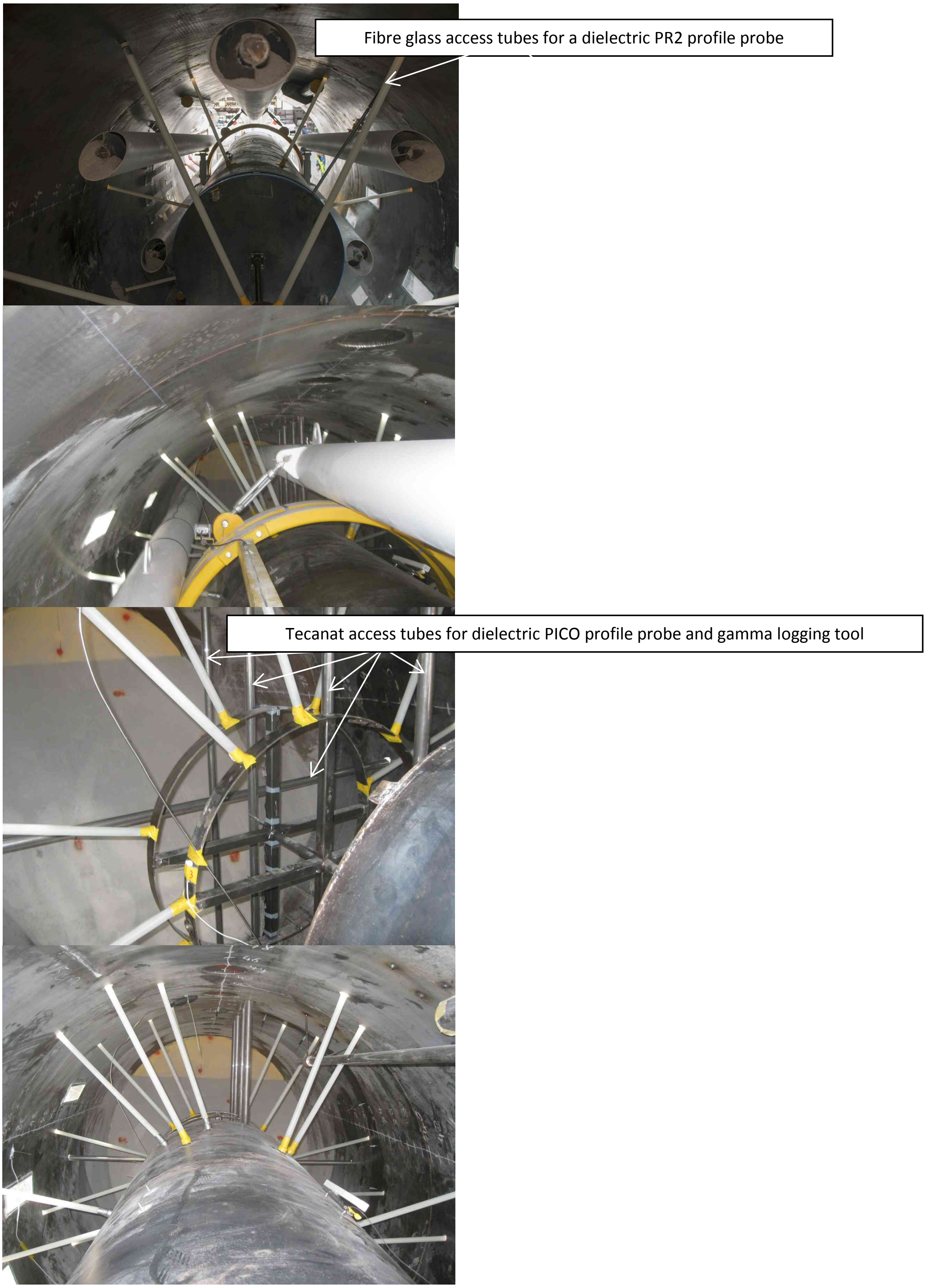


Figure 19: Photos with access tubes for different local density estimation methods.

In the upper pictures, access tubes for "PR2" profile probes from Delta-T Ltd are indicated (L = 115 cm). The arrows in the lower pictures point to access tubes for "PICO" profile probes (L = 300 cm) which were also used for gamma-gamma logging.

Figure 20: Photos through observation windows in the steel liner of the dummy tunnel showing variations of segregation effects.

### 3.3.2 Density results from mass-volume balance

The density results derived from mass-volume balance are listed in Table 2. Taking into account the inaccuracy of the method, the average dry density values are between 1.48 and 1.55 t/m$^3$.

Table 2: Dry density results in [t/m$^3$] calculated from mass-volume measurements.

Values for inaccuracy result from conservative assumption of:

- 0.35 % due to weighing inaccuracy and 2.5 kg material loss per bigbag
- Standard deviation in water content measurements (5.54 ± 0.16 % for Mock-up 1 and 5.60 ± 0.09 % for Mock-up 2)
- Inaccuracy in volume estimation (1 % for Mock-up 1 and 0.2 % for Mock-up 2)
- Inaccuracy in positioning of the survey (± 0.01 m$^3$)

| **Values [t/m$^3$]** | **Mock-up 1** | **Mock-up 2 gap** | **Mock-up 2 around canister** | **Mock-up 2 total** |
|---|---|---|---|---|
| Average dry density | 1.498 | 1.490 | 1.525 | 1.502 |
| Inaccuracy | ± 0.023 | ± 0.013 | ± 0.022 | ±0.009 |

### 3.3.3 Density results from gamma-gamma measurements

Density profiles from gamma-gamma logging are shown in Figure 21. The three profiles to the left represent horizontal profiles in the longitudinal direction ("bottom PICO" and "roof PICO") and in the transverse direction, just beyond the dummy canister ("transverse PICO"). The four profiles to the right were logged in the vertical direction. These vertical profiles were double-checked by additional loggings (red and black lines), providing proof of the good reproducibility of the method.

The V1-V4 profiles indicate relatively high (moist) densities ρ along the first half metre near the tunnel roof (ρ = 1.7 to 1.8 t/m$^3$, corresponding to dry densities $\rho_d$ of 1.6 to 1.7 t/m$^3$ with respect to an average water content around 5.5 %). The density decreases by 0.1 t/m$^3$ to ρ = 1.6 – 1.7 t/m$^3$ ($\rho_d$ = 1.5 – 1.6 t/m$^3$) for the major backfilled volume.

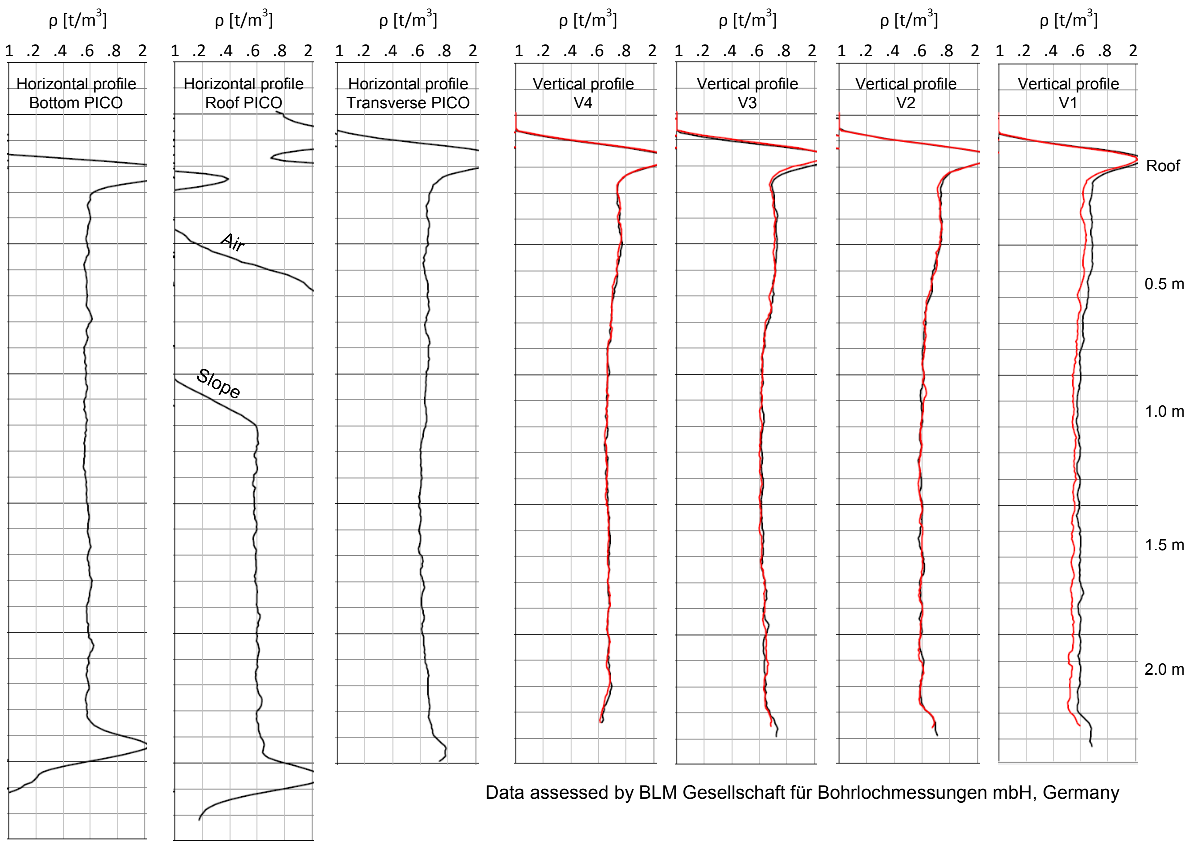


Figure 21: Density profiles from gamma-gamma measurements.

### 3.3.4 Density results from dielectric measurements

Dry density profiles resulting from dielectric measurements with a PR2 probe are shown in Figure 22 and Figure 23. Maximum values near the screw conveyor positions and lower values between them can be identified here. Measurement profiles installed in the top part show a higher average value than bottom profiles. However, boundary effects yielded a significant decrease in dry density values towards the steel tunnel liner, which is not consistent with observations from the other methods.

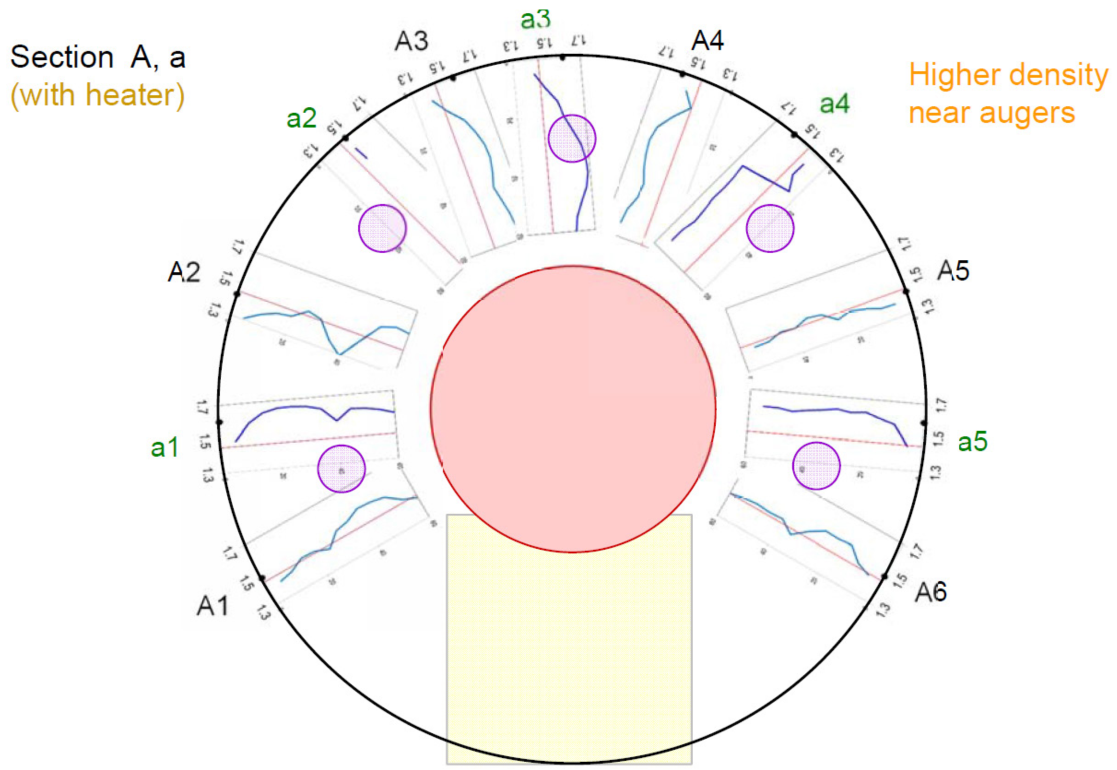


Figure 22: Dry density profiles derived from dielectric profile measurements around the dummy canister.

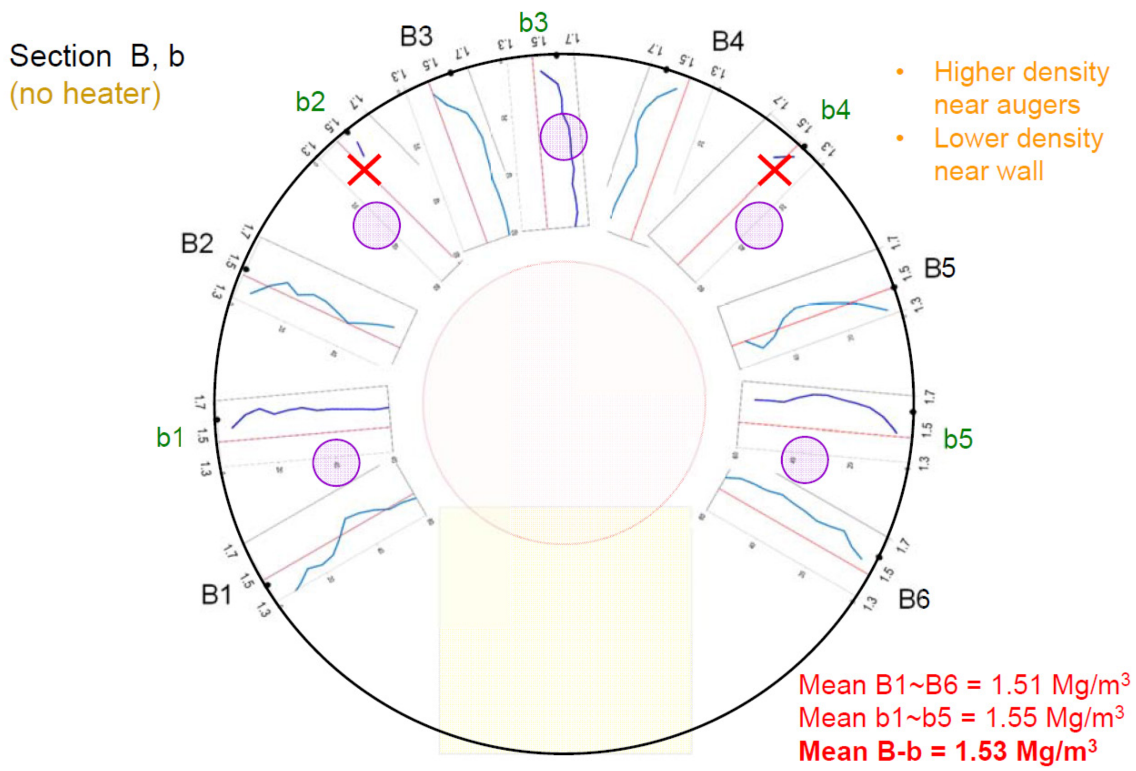


Figure 23: Dry density profiles derived from dielectric profile measurements beyound the dummy canister (no results from the centre with this method due to geometric constraints (limited length of the access tubes and the profile probe)).

### 3.3.5 Density results from cone penetration tests (CPT)

Dry density profiles resulting from CPT are shown in Figure 24. They are ordered in such a way as to allow comparisons with respect to the position of the profile. A tendency towards higher density is obvious, the higher the profile lies in the cross-section. Most of the profiles show values for dry density between approximately 1.50 and 1.65 $t/m^3$, but, towards the tunnel invert, relatively low cone resistances were measured, yielding values around 1.40 $t/m^3$.

Results from dielectric measurements at corresponding positions close to the respective position in the profiles are indicated by red points to allow comparison between these two methods. See Figure 18 for the positions of all CPTs.

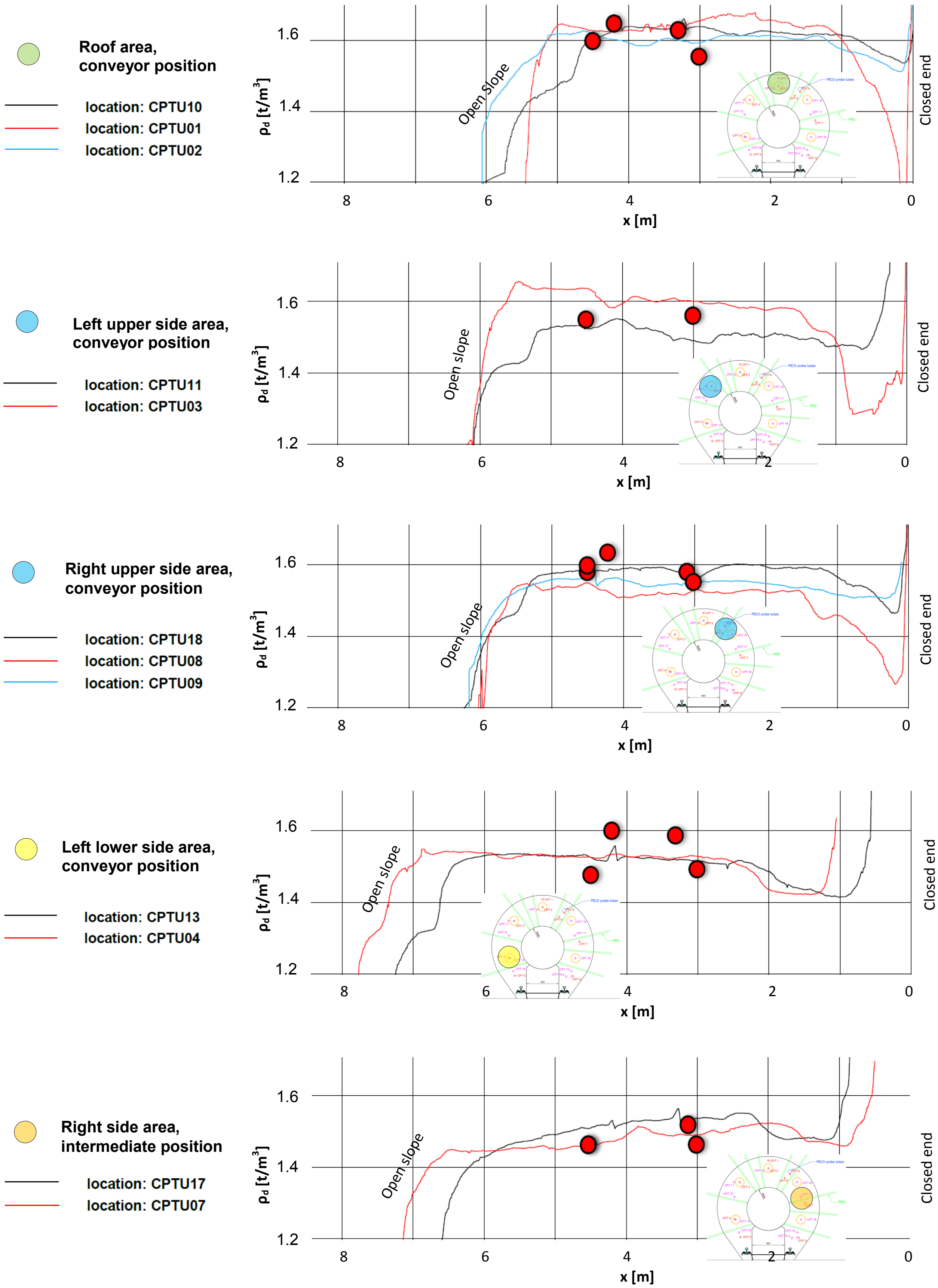


Figure 24: Dry density profiles derived from horizontal cone penetration testing (CPT).

● Corresponding dry density value from PR2 profile close to the respective position.

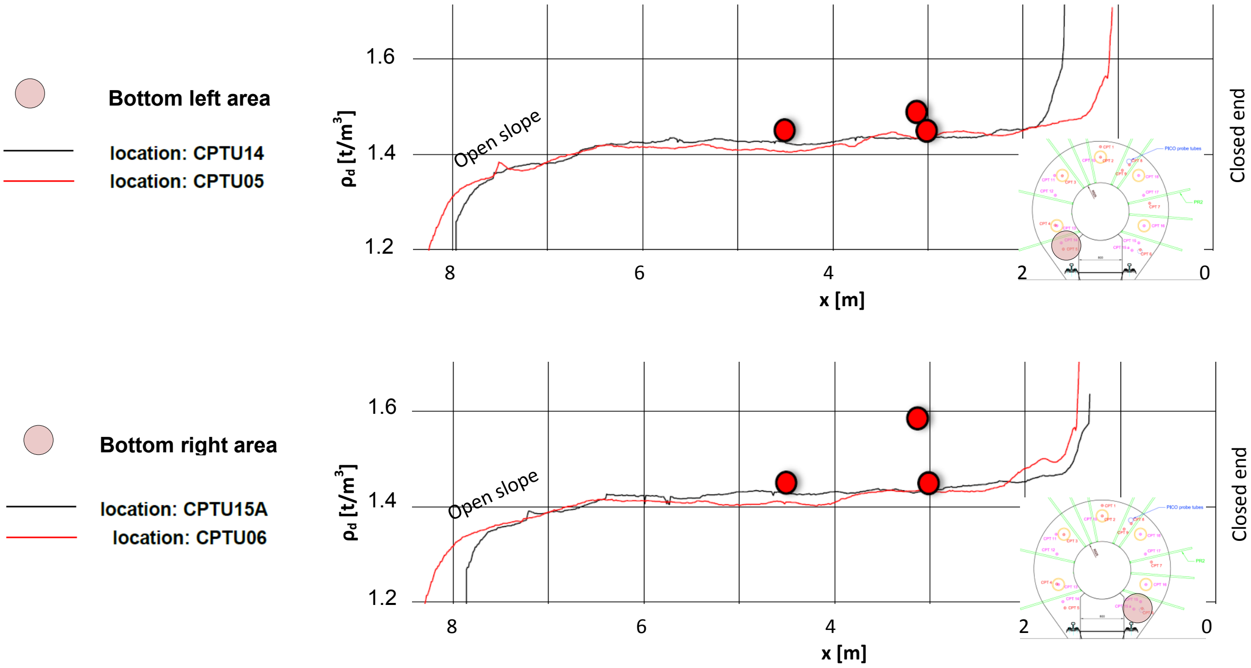


Figure 24: (continued)

# 4 Emplacement at the Mont Terri URL

The backfilling timeline for the FE as a function of gallery metres (GM) is presented in Figure 25. The dates and duration of each of the activities are indicated. The deep end of the tunnel was filled with porous concrete. Adjacent to the porous concrete end plug, a bentonite block wall (BBW) was built in the interjacent sealing section (ISS). The rest of the ISS was filled with GBM in 4 days. After this first part, the three heaters were emplaced and backfilled in an iterative process. The backfilled tunnel was closed by a retaining wall built stepwise to allow backfilling of the last cubic metres with GBM. Finally, a 5m long concrete plug was poured to ensure water- and airtightness of the test section and to contain potential bentonite swelling. A detailed event description can be found in Müller et al. (2015).

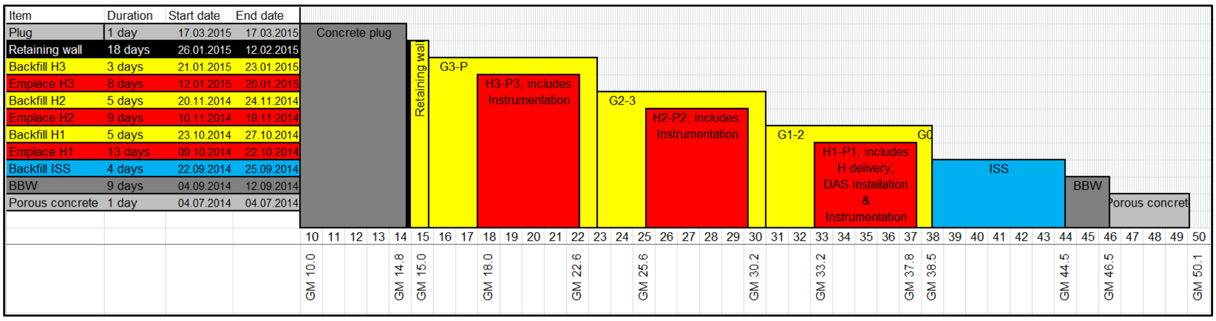


Figure 25: FE backfilling timeline.

## 4.1 Construction of the bentonite block wall

In the current Swiss reference concept, interjacent sealing sections are planned to be installed at every 10th waste canister position in order to intercept potential preferential axial flow paths for radionuclides (Nagra 2010). In the FE Experiment, a 2 m long bentonite block wall[1] was constructed in the ISS to:

- Investigate what bentonite dry density can reasonably be expected with bentonite blocks assembled in a representative tunnel section
- Verify the construction feasibility of such a wall on a layer of compacted granulated bentonite considering the irregular tunnel surface
- Be able later on to measure the sealing effectiveness of the wall

The construction was done manually to allow the emplacement of a number of sensors. The sensors and saturation lines installed in the porous concrete section behind the wall will allow later measurement of the sealing effectiveness. The compacted GBM layer (Figure 26, left) proved to be sufficiently stable for the construction of the bentonite block wall (Figure 26, right). The bentonite blocks were designed to resist the ambient conditions at Mont Terri (a relative humidity of more than 80 % might have destroyed the blocks). During the two weeks of installation, no block disintegrated and the wall remained stable throughout.

[1] The current Swiss reference concept requires neither the construction of a bentonite block wall in the ISS nor the implementation of higher bentonite dry density compared to the backfill around the waste canisters. However, such bentonite block walls are an option, especially with regard to other sealing structures in a geological repository for radioactive waste.


Figure 26: Bentonite block wall in the ISS (during construction: right), constructed on a compacted layer of GBM.

The volume occupied by the bentonite block wall was equal to 14.658 $m^3$ (based on a tunnel scan with a resolution of 5 mm), including the volume occupied by the compacted floor. The dry density was calculated as:

*[Mblocks/(1+wc blocks) + MGBM/(1+wc GBM)]/volume BBW*

where:

- *Mblocks* = 26029 kg
- *Water content blocks* = 18 %
- *MGBM* = 2789 kg
- Water content GBM = 6 %
- *Volume BBW* = 14.658 $m^3$

Ignoring the measurement error of the mass, which is relatively small compared to the BBW volume measurement, the relative error of the calculated dry density is 2.92 %. The determined BBW dry density is: 1.69 ± 0.05 g/$cm^3$.

## 4.2 Emplacement procedure

The emplacement and backfilling principle for a single heater (dummy disposal canister) in the FE Experiment is shown in Figure 27, starting with the slope of the preceding backfill (a temporary retaining wall made of wooden formwork panels helped to maintain a working space of 80 cm width between the slope and the heater position for the subsequent instrumentation work around the heater).

In the first step, the bentonite pedestal was assembled iteratively with bentonite blocks on a pre-pared concrete surface and instrumented with sensors. This work was done manually inside the tunnel, not exhibiting any demonstration character with respect to the reference emplacement concept in a repository (Figure 28).

Next, the heater was driven into the tunnel and over the bentonite pedestal with an emplacement wagon especially designed for the FE Experiment (Figure 29 to Figure 291).

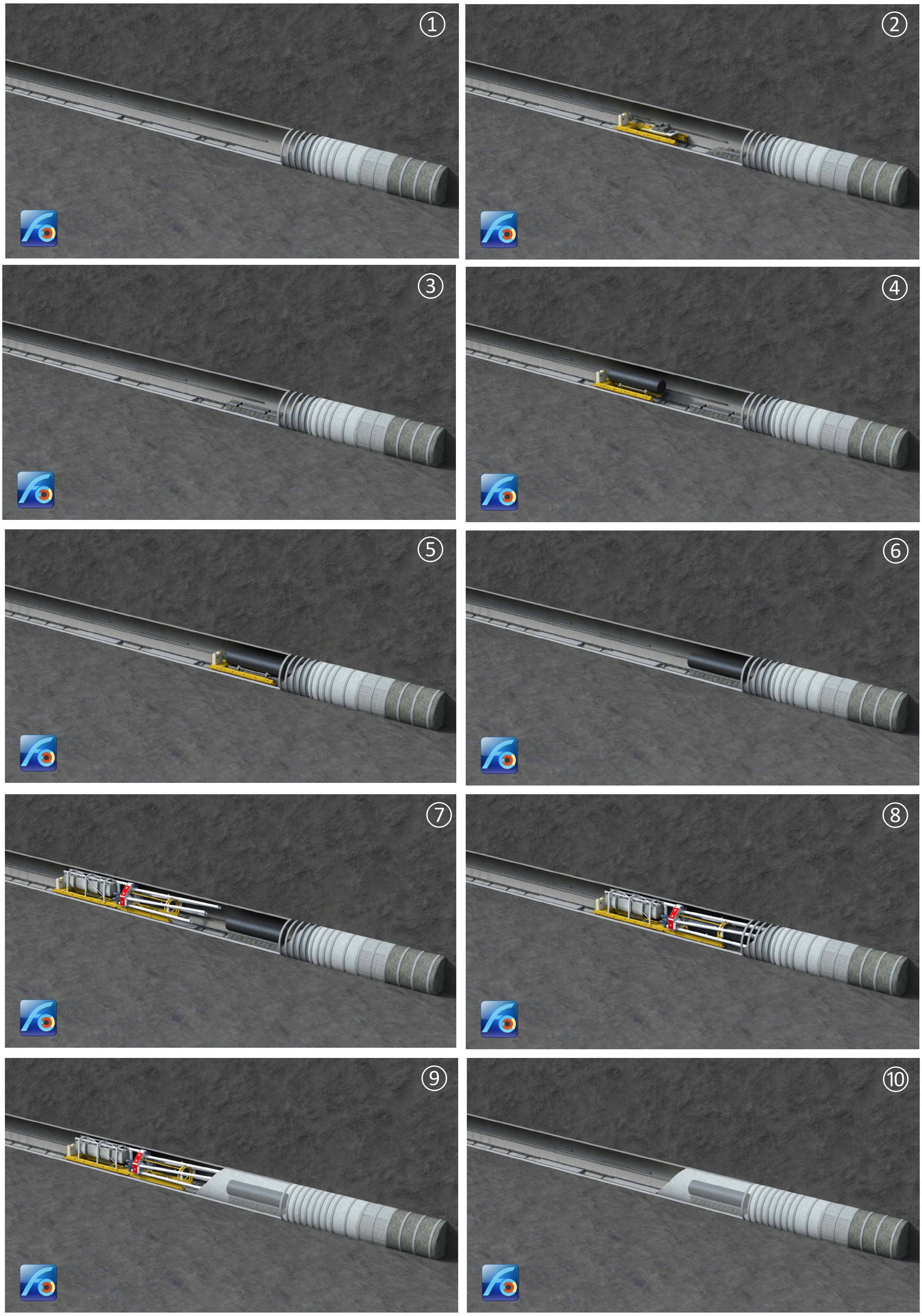


Figure 27: Work sequence for the emplacement of the first pedestal, heater and respective backfill. This procedure was repeated for the emplacement of each heater element

Figure 28: Photos from the manual assembly of the bentonite block pedestal.


Figure 29: Photos of heater No. 2 being loaded onto the emplacement wagon.

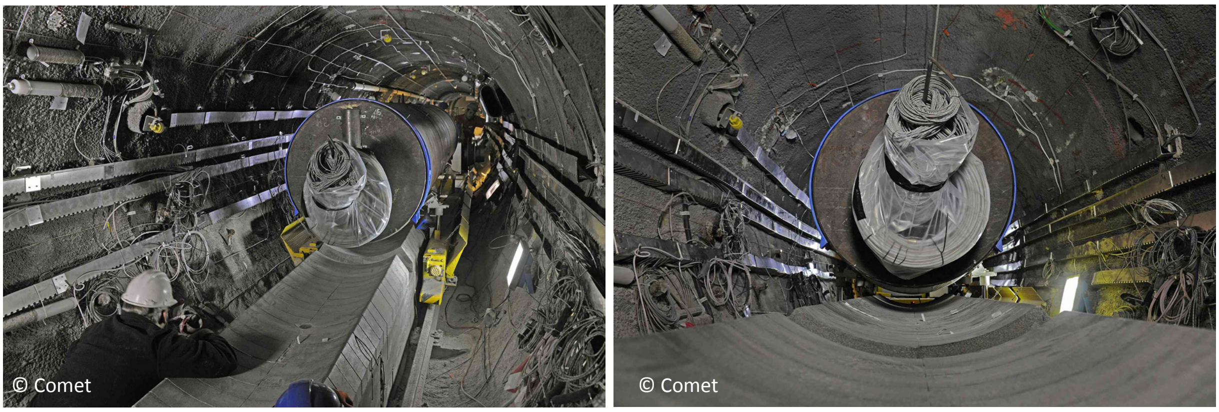


Figure 30: Photos of heater No. 2 being emplaced on the bentonite pedestal.


Figure 291: Photos after completion of the emplacement of heater No. 2.

After completion of the heater emplacement, the backfilling machine drove over it so that the screw conveyor tips were inserted into the bulk material and started backfilling in a retreating mode (Figure 302 and Figure 313, left). The feeding wagon contained approximately 4 t of backfill material, which corresponds to ca. 0.5 m to 0.75 m of backfilled length in the tunnel. To complete the whole sequence for a single canister backfilling, around sixty 1-t bigbags had to be backfilled and the feeding wagon had to be reloaded 15 times. This was done 70 – 80 m back at the intersection of the MB niche and Gallery 08, while the backfilling unit remained in the FE tunnel with the screw conveyor tips inserted into the bulk material (Figure 313, right). Further disruptions resulted from the need to install sensors immediately in front of the proceeding slope, as well as from QC measures. This sequence was repeated for each of the three heaters.

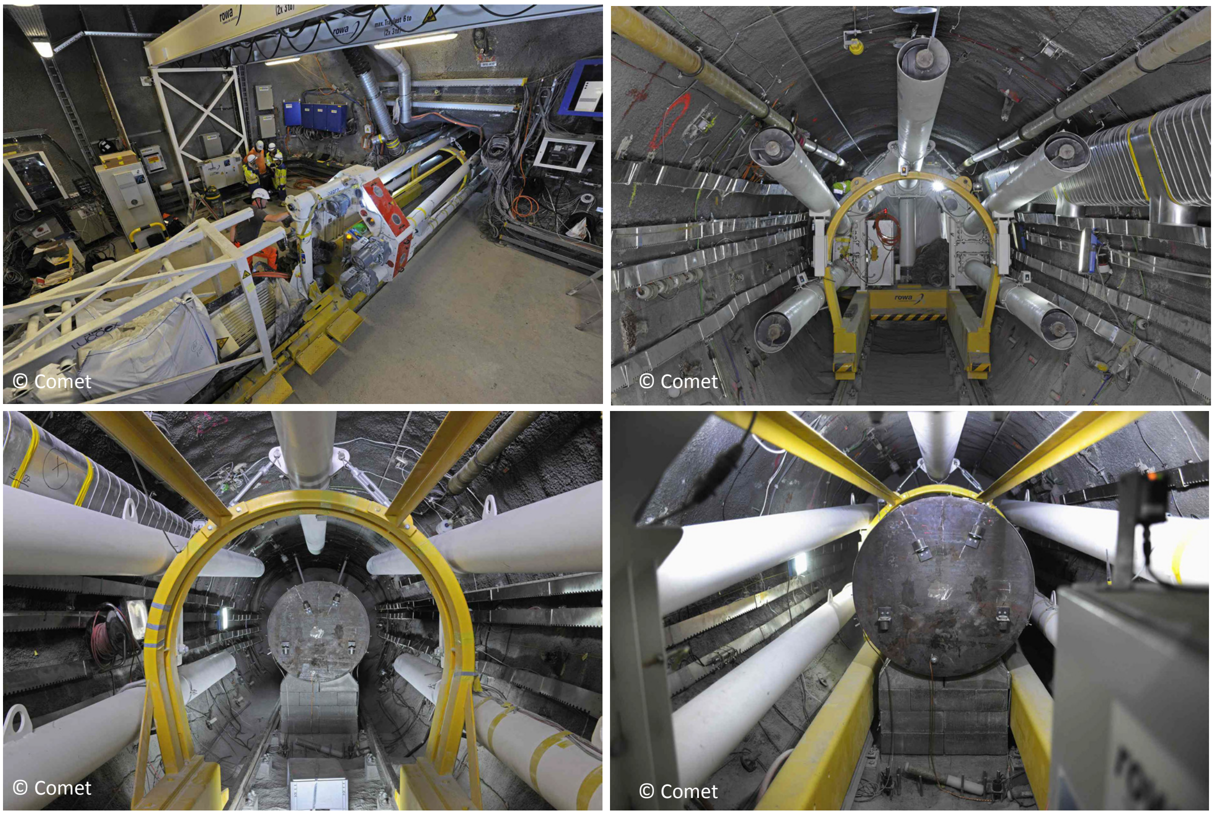


Figure 302: Photos of the backfilling machine driving over heater No. 2.


Figure 313: Photos of the backfilling operation in the tunnel (left) and reloading bigbags onto the feeding wagon (right).

For reloading, the feeding wagon was detached from the backfilling unit and driven ca. 70 m to 80 m back to the junction of the MB niche and Gallery 08.

## 4.3 QC methodology by mass-volume balance

Due to the limited access compared to the mock-up tests, estimation of the local density was not possible to a comparable level of refinement, so the QC was limited to the mass-volume balance method.

For a record of the backfilled mass, every bigbag was weighed on a pallet truck incorporating a weighing unit with ± 2 kg accuracy. Dead weight such as pallets, empty bigbags and material samples were subtracted from the recorded weight. On the other hand, amounts of backfill material that were manually transferred into the FE tunnel were weighed and also recorded (e.g. the very first section covering the base of the bentonite block wall, but also manual fillings of cable channels and hollow parts of extensometer pipes, etc.).

As mentioned before, the complete backfilling machine had to be pulled out of the FE tunnel eleven times in order to install various sensors and cables across the tunnel profile, just in front of the proceeding backfill slope. Since free access to the backfill slope provided a good opportunity for QC, slope surface scans were conducted in order to calculate the backfilled volume separately for each section between such interrupted backfilling stages.

The volume between two slopes was calculated after each scan. The basis for the volume calculations was a tunnel scan. Scans with a resolution of 5 mm were used. Shading objects such as rails, cable channels, pipes and measuring tapes were removed from these tunnel scans to increase the accuracy of the cubature calculation. The next step involved modelling a 3D point cloud for each slope from the basic scans and the slope scans (Figure 324).

This 3D point cloud was then cut every centimetre and the interpolated cubature between these cuts was calculated. Objects that were larger than 1 $dm^3$ and which had been covered by the backfill were subtracted from the sum of the calculated cubature of the slopes. This included the heater, pedestal and rail section, as well as cables in the cable channels and pipes (except for the hollow volume of extensometers and cable channels which had been manually filled with bentonite).

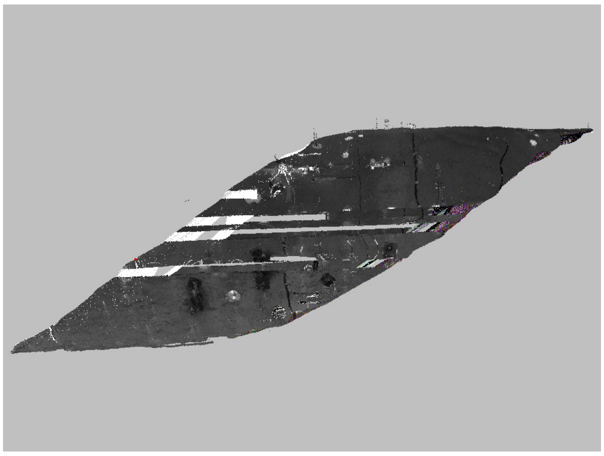

Figure 324: Slope scan with geodetic total station Leica MS50 (left) and point cloud (right) resulting from the synthesis of a basic tunnel scan and two adjacent slope scans

Finally, distinct dry densities were calculated from the ratio of mass and volume per section using the following formula:

$$\rho_d = \frac{m}{V \cdot (1+w)} \qquad [t/m^3]$$

$\rho_d$: dry density [$t/m^3$]
m: weight [t]
V: volume [$m^3$]
$w = (m-m_d) / m_d$: water content, defined as weight of water loss during oven drying divided by the weight of the dry sample

## 4.4 Quality control: Density results from mass-volume balance

The dry densities resulting from sectional mass-volume calculations are listed in Table 3 and depicted graphically in Figure 35. The values originating from the backfilling with the five screw conveyors (slopes 1 to 11) range from 1.444 to 1.555 t/m$^3$. In the section covered by slope No. 10, low quality material consisting only of very fine powder happened to be backfilled; this problem was only recognised when the material had already been backfilled into the tunnel.

The last part behind the vertical retaining wall indicates a significantly lower density. This is most likely due to incomplete backfilling in the upper side wall areas.

Table 3: Average dry density results in [t/m$^3$] per section calculated from mass-volume measurements.

The deviation is estimated to be 0.007 t/m$^3$, resulting from the assumption of 0.35 % material loss and weighing inaccuracy plus 0.1% volume estimation inaccuracy. However, local heterogeneity could not be recorded, but is expected to be similar to the mock-up tests.

| **Section** | **Wall TM 15** | **Slope 11** | **Slope 10** | **Slope 9** | **Slope 8** | **Slope 7** | **Slope 6** | **Slope 5** | **Slope 4** | **Slope 3** | **Slope 2** | **Slope 1** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Local dry density [t/m$^3$] | 1.403 | 1.477 | 1.444 | 1.555 | 1.530 | 1.496 | 1.519 | 1.494 | 1.487 | 1.474 | 1.495 | 1.496 |

The overall dry density calculated from the whole mass-volume ratio and the average from the sectional calculations is 1.489 ± 0.003 t/m³. Between slopes 3 and 9, which can be considered representative of routine emplacement, the average dry density is 1.513 ± 0.003 t/m³. The required dry density of 1.45 t/m³ was clearly exceeded.

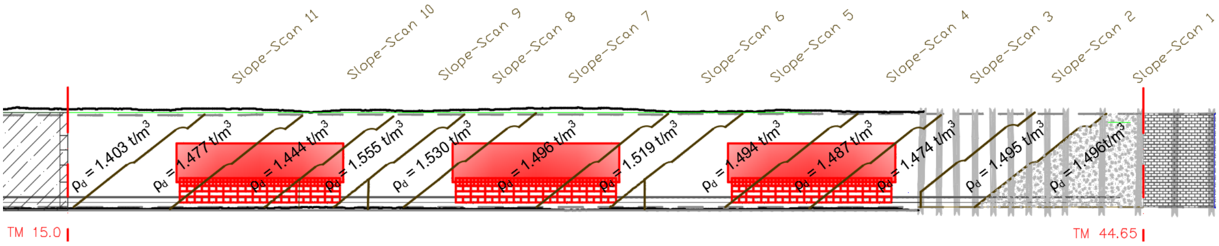


Figure 35: Illustration of average dry density results per section

# 5 Lessons learned

During backfilling, signs of wear of the screws that were obviously caused by friction on the conveyors' steel tubes were noticed. The backfilling operation was not negatively affected, however. After completion of the backfilling operation, the most affected screw was dismantled and examined (Figure 336).

The signs of wear obviously occurred progressively over one metre, starting from the tip being pressed upwards onto the tube walls while conveying. The reason for this is the vertical component of the reaction force from stuffing the bulk material. The vertical force occurs due to the oblique shape of the conveyor tubes' tips which are intended to push material upwards to backfill potential gaps and overbreak in the uneven tunnel profile. For next-generation screw conveyors, it is advisable to design the augers more resistant to bending.

Some bigbags containing low quality bentonite material were noticed too late. This caused low density backfill in the section covered by slope No. 10. It is assumed that this happened due to insufficient QC. Onsite QC was limited to collecting samples from every bigbag during the backfilling process. Additional checks by opening each bigbag before backfilling would have been relatively inefficient since only the surface of the bulk material is manually accessible and visible. Therefore, QC must rely on the production and packing of the backfill material. However, the poor material in question originates from the mock-up tests. The packing for reuse had been temporarily unsupervised.

Figure 336: Signs of wear from friction between screw conveyor screw and the top part of the screw conveyor tube due to the oblique cut of the tube tip resulting in a vertical reaction force component and corresponding deflection.

Note that the very front part of the screw is not affected because it had not been pressed against the conveyor tube due to the oblique shape of the tube tips.

# 6 Conclusions and outlook

Backfilling operations at the Mont Terri URL and at the pre-testing sites were achieved without any accidents or serious breakdowns.

In total, 255 tons of granulated bentonite mixture and 39 tons of bentonite blockswere backfilled in the FE tunnel at Mont Terri. The average dry density of the GBM is 1.489 ± 0.003 t/m$^3$. A bentonite block wall was built in the ISS with an average dry density of 1.69 ± 0.05 g/cm$^3$. The dry density of the bentonite block pedestals supporting the heaters is close to the block dry density (1.78 g/cm$^3$). The target dry density of 1.45 t/m$^3$ for the entire backfill was clearly met.

Pre-test B showed segregation of the GBM during backfilling. There is certainly potential for optimisation regarding homogeneity and density of the horizontal backfill with the horizontal screw conveyance method (e.g. number and size of augers, implementation of compression tools and slope coverage). In the FE project, segregation was limited by optimising the mixture design, which has a grain size distribution characteristic of self-compacting mixtures.

Various methods for local dry density assessment were applied, especially in the mock-up tests where radial access from outside the dummy tunnel tube was possible. The resulting profiles of local dry density indicate higher values near the roof section and in the close vicinity of the screw conveyor positions. Lower density was observed near the invert. Certain open questions remain, e.g. regarding boundary effects with PR2 dielectric measurements. In general, however, the results show good consistency. This is also valid for the comparison with the average dry density resulting from the mass-volume balance (1.48 to 1.55 t/m$^3$).

The sectional dry density values assessed in the FE tunnel at Mont Terri by mass-volume balance varied between 1.444 t/m$^3$ (where two bigbags of low quality material were backfilled) and 1.555 t/m$^3$.

However, the conveyor screws showed significant signs of wear. For a next-generation backfilling machine or for industrial application in a radioactive waste repository at the latest, this issue should be addressed.

Future work will be in line with Nagra's upcoming RD&D plan that is currently being prepared. In the context of buffer and backfill emplacement, the focus will be on the estimation and analysis of local dry density variations, as well as on mitigation of these variations by innovative process engineering with regard to further improvement of the buffer / backfill quality.

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