Horizontal bentonite backfilling and concrete plug for the Full-Scale Emplacement (FE) Experiment at the Mont Terri URL: requirements, design, instrumentation and emplacement

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The Full-Scale Emplacement (FE) Experiment at the Mont Terri underground rock laboratory (URL) is a full-scale multiple heater test in Opalinus Clay. According to the Swiss disposal concept, it simulates the construction, waste emplacement, backfilling and early post-closure evolution of a spent fuel (SF) / vitrified high-level waste (HLW) emplacement tunnel as realistically as possible. The main aim of the experiment was to investigate repository-induced thermo-hydro-mechanical (THM) coupled effects on the host rock at this scale and to validate existing coupled THM models. The construction of the 50 m long experiment tunnel with a diameter of approx. 3 m was completed in September 2012. The backfilling of the FE tunnel, Figure 1, was carried out between July 2014 (emplacement of a porous concrete plug at the back end of the tunnel) and March 2015 (closure of the experimental section with a concrete plug).

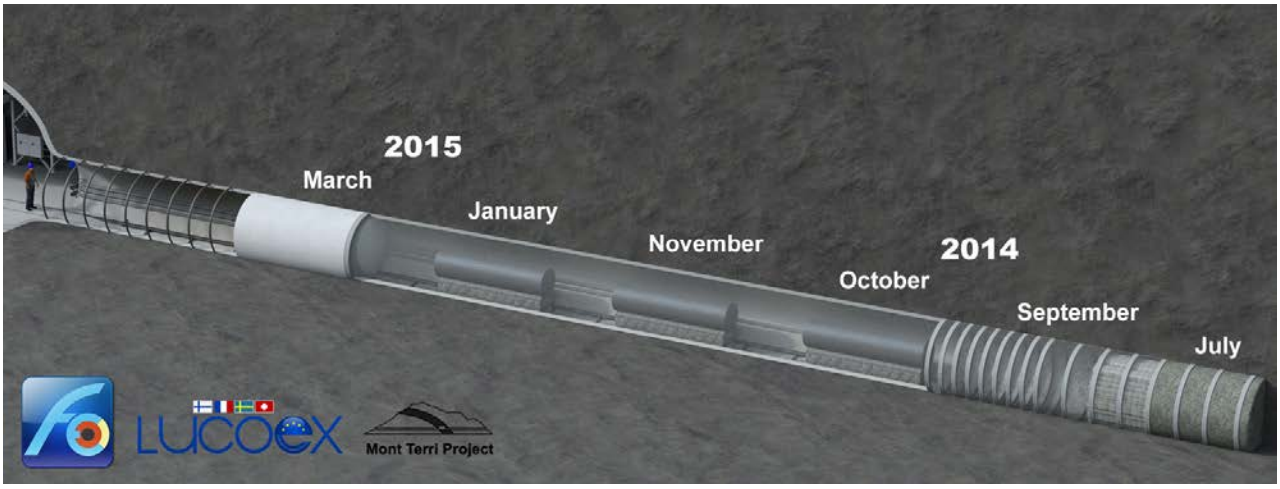

Figure 1: Visualisation of the FE/LUCOEX experiment at the Mont Terri URL (backfill not shown)

In the FE tunnel, three heaters with dimensions similar to those of waste canisters were emplaced on top of pedestals built of bentonite blocks between October 2014 and January 2015. The remaining space was backfilled with a granulated bentonite mixture (GBM) using a prototype machine with 5 screw conveyors developed for this purpose. The main requirement related to the emplacement dry density. Based on correlations observed between the emplacement dry density and other key parameters such as the hydraulic conductivity, the swelling pressure and the thermal conductivity, a minimum dry density of 1.45 t/m^3 was targeted. This was also found to be the threshold for microbiological activity (Stroes-Gascoyne, 2011). Finally, in February and March 2015, the experiment was sealed off with a 5 m long concrete plug holding the bentonite buffer in place and reducing air and water fluxes. The paper describes the quality control of the dry density during the horizontal emplacement procedure for underground conditions and the design and construction of the friction plug emplaced to close the experimental section. The FE plug has no demonstration character, but the lessons learned have relevance for the design and construction of future repository plugs, as well as for other experimental plugs.

Horizontal backfilling

The range of possibilities for backfill materials was assessed for the FE Experiment. After selecting natural sodium bentonite from Wyoming and several parameter optimisation tests, approx. 350 tons of a granulated bentonite mixture (GBM) were produced in Germany. The GBM consisted of highly compacted bentonite granules with an average particle dry density of 2.18 t/m^3. After production by roller presses, the granules were mixed and sieved to achieve a very broad grain size distribution, a so-called Fuller-type distribution. The production processes are described in a companion paper (Garitte et al., 2016) and in Garitte et al. (2015).

Based on experience from preceding projects and on extensive pre-testing (Köhler et al., 2015), a prototype backfilling machine was designed and manufactured (Figure 2). This machine transports, emplaces and compresses the granulated bentonite mixture in horizontal small-diameter tunnels as densely and homogeneously as possible using five screw conveyors, without applying additional compaction. It was tested extensively in a surface industrial facility before using it underground in Mont Terri.

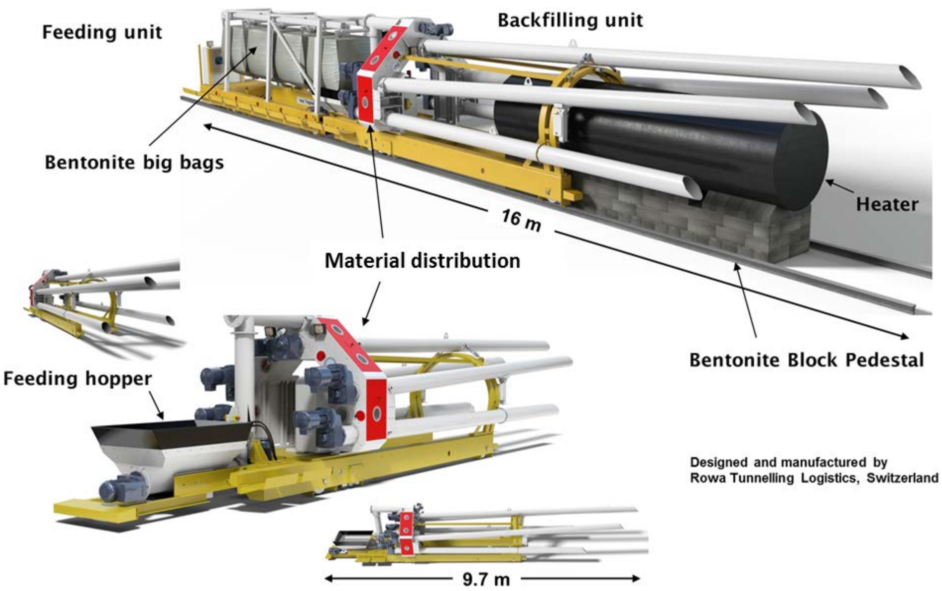

Figure 2: The backfilling machine for the FE Experiment

Mock-up tests were conducted to check and optimise the technology in a set-up representative for the conditions at Mont Terri. All relevant parameters, such as the backfilling speed and the backfilling pressure, were checked in the off-site tests. Process-related interfaces such as the geometries of other components (tunnel walls, bentonite pedestal and heater, sensors and cables, etc.) were also investigated (Figure 3).

Figure 3: Photo of the rear end of the backfilling machine ready to start backfilling the steel tunnel tube

The off-site tests offered the possibility to perform a detailed quality control (QC) of the backfill, which is not conceivable in an underground facility. Different methods for local density assessment such as slope laser scanning, dielectric tools, gamma-gamma logging and cone penetration testing were developed. The local dry density values derived from these methods range from 1.4 to 1.7 t/m^3. Generally, they show good consistency and allow the homogeneity of the emplacement to be characterised (Figure 4). This characterisation allowed a higher dry density zone in the area of the screw conveyor tips to be identified.

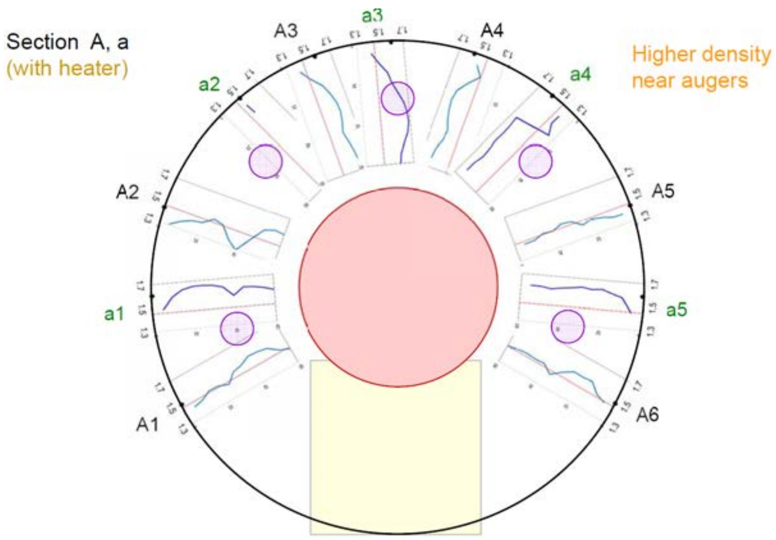

Figure 4: Dry density profiles derived from dielectric profile measurements around the dummy canister

Emplaced volume estimation was performed by geodetic laser scans of the slopes (Figure 5). Sectional values for dry density from mass-volume balance calculations were between 1.48 and 1.55 t/m^3 (Table 1). The off-site mock-up tests provided an opportunity to optimise the measurement methodology and to develop protocols for calculating the measurement error. The error calculation given in Table 1 is based on the following conservative assumptions:

- 0.35 % due to weighing inaccuracy and 2.5 kg material loss per bigbag of approx. 700 kg
- 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 m3)

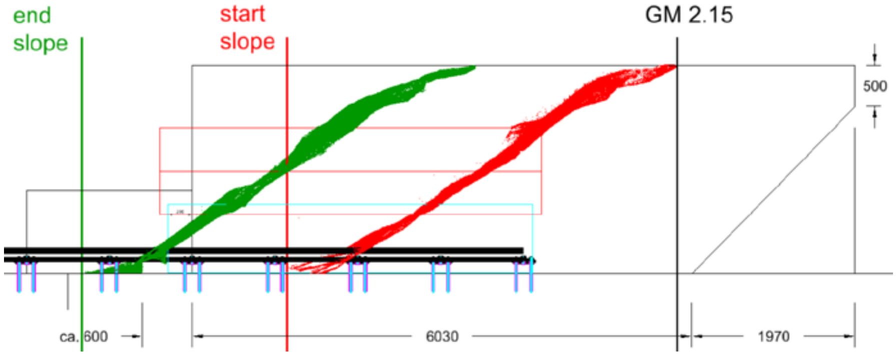

Figure 5: Slope scans for distinct volume estimation around the dummy canister and beyond

Table 1: Dry density results in [t/m3] calculated from mass-volume measurements

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
Measurement error	± 0.023	± 0.013	± 0.022	±0.009

With the FE Experiment, it was possible to demonstrate that, using a GBM and a suitable backfilling machine, an overall bulk dry emplacement density of at least 1.45 t/m^3 (as targeted for this experiment) can be achieved in horizontal emplacement tunnels in Opalinus Clay. The overall dry density measured in the on-site test was 1.489 ± 0.003 t/m^3. Following the methodology developed off-site and using a 3D volume scan of the tunnel, the variation in the dry density along the tunnel axis was measured in 12 sections of the FE tunnel (Figure 6). The measured variation along the tunnel axis is relatively small and only volume no. 12 (close to the retaining wall) is characterised by a measured dry density significantly lower than the target value. Filling of this volume had to be performed in steps, whereby the lower screw conveyors of the backfilling machine were removed while the retaining wall was constructed. In sectional volumes 4 to 11, which can be considered representative of routine emplacement, the average dry density is 1.513 ± 0.003 t/m^3.

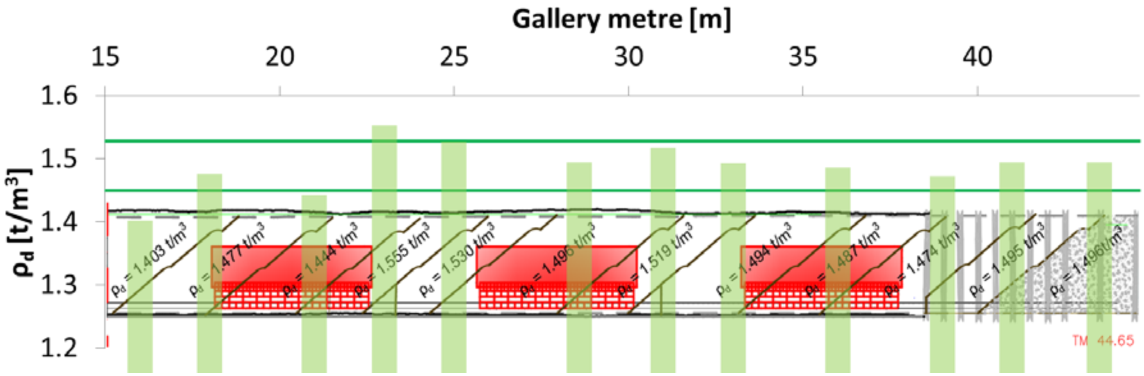

Figure 6: 12 sectional volumes along the FE tunnel axis in which the dry density was calculated from mass-volume measurements. Sectional volume 1 is at the back (right) end of the tunnel and Sectional volume 12 is at the front (left) end of the tunnel

Concrete plug

The FE plug was designed to withhold the potential swelling pressure of a fully saturated bentonite backfill of approx. 3.5 MPa for an average bulk dry density of about 1.45 t/m^3 and to limit water and air fluxes between the experimental zone and the open tunnel system. The plug design was aimed at limiting the fluxes through the concrete, at the interface between plug and shotcrete and through the EDZ (Q1, Q2 and Q3 in Figure 7), but also around the cable bundle (750 cables) that was routed through the plug.

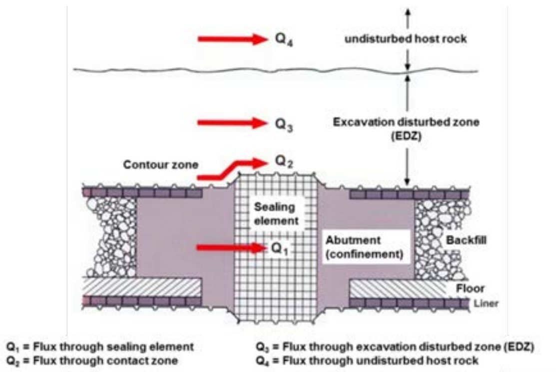

Figure 7: Potential fluxes through a sealed section. Note: in the FE experiment, the shotcrete lining was not removed because of the risk of destroying the instrumentation cables

The plug was designed as a friction-controlled plug. 50 steel dowels were installed radially through the rock - shotcrete - plug interface to increase the shear resistance at the concrete-shotcrete interface. Each of the dowel boreholes was injected with resin in order to seal the EDZ around the plug. Approx. 29 m^3 of self-compacting concrete were pumped into the space between the 20 cm thick retaining wall erected at tunnel metre (TM) 15 and the formwork placed at TM 9.8. In order to limit the curing temperature of the concrete to a maximum of 50°C, 60% of the Portland cement was replaced by fly ash and microsilica. 40 days after casting, the shrinkage gap at the plug / shotcrete interface was injected with resin with a pressure of approx. 5 bar to seal the interface. The theoretical estimation of the shrinkage gap was less than 1 mm (resulting from a measured concrete shrinkage of approx. 0.02%). However, although a highly flowable concrete was used, an air pocket remained at the top back end of the plug. This air pocket was clearly identified from the volume of resin injected to close the shrinkage gap and by continuous qualitative water content measurements through TDR cables installed around the tunnel wall perimeter.

The oxygen concentration monitored in the GBM backfill showed a rapid decrease (Figure 8). The oxygen sensors close to the retaining wall did not decrease to zero, differently to further distant sensors. The residual oxygen concentration in these sensors varied and this variation could be clearly correlated to atmospheric pressure variations in the entrance tunnel. Despite the fact that the plug was installed with the highest possible care to improve its sealing properties, a full disconnection could thus not be achieved. The most probable explanation is the difficulty of correctly sealing the 750 instrumentation cables routed through the plug.

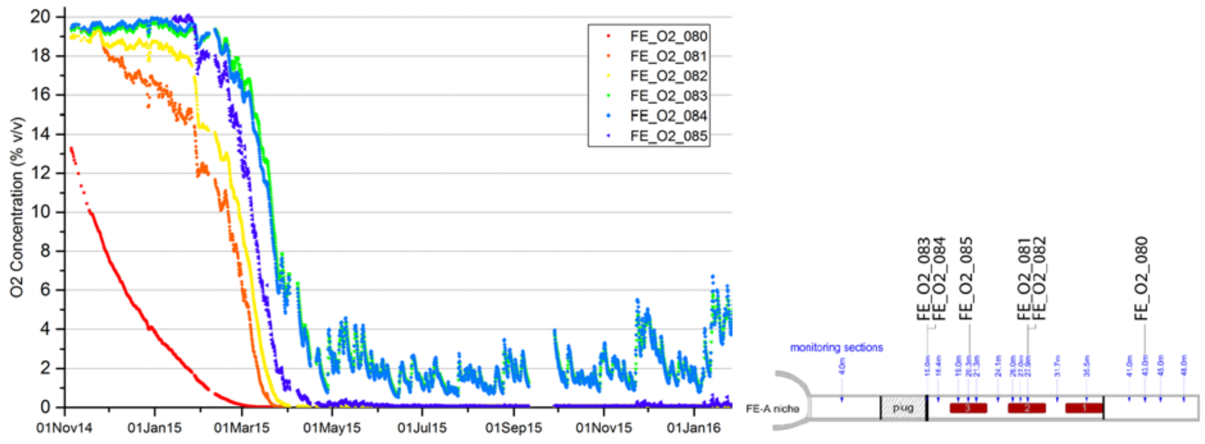

Figure 8: Oxygen concentration measured in the GBM backfill at several distances from the retaining wall

Acknowledgments

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