Bentonite-based materials for the Full-Scale Emplacement (FE) experiment: design and production steps

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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 (Figure 1). 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. A granulated bentonite mixture (GBM) and highly compacted bentonite blocks were used to backfill the FE tunnel. The raw bentonite material and the production of the GBM were contracted by public tendering according to World Trade Organization standards (Garitte et al., 2015). Approx. 350 tons of raw bentonite (National ® Standard WP2) were transformed into a GBM. The aim of the GBM production process is to increase the loosely poured bulk dry density of the raw bentonite material, which is approx. 1.0 g/cm^3, to an emplacement dry density of 1.45 g/cm^3 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 g/cm^3 was also found to be a threshold for microbiological activity (Stroes-Gascoyne, 2011). In the FE experiment, the heaters were placed on top of compacted bentonite block pedestals. A 2 m long section of the interjacent sealing section was backfilled with compacted bentonite blocks (sealing sections in emplacement tunnels have been proposed as an option for the Swiss concept, replacing every tenth canister, with steel arch rock support instead of shotcrete rock support (Nagra 2010)). The production of 2500 rectangular and 500 curved "top layer" blocks (approx. 70 tons in total) is described in the second section.

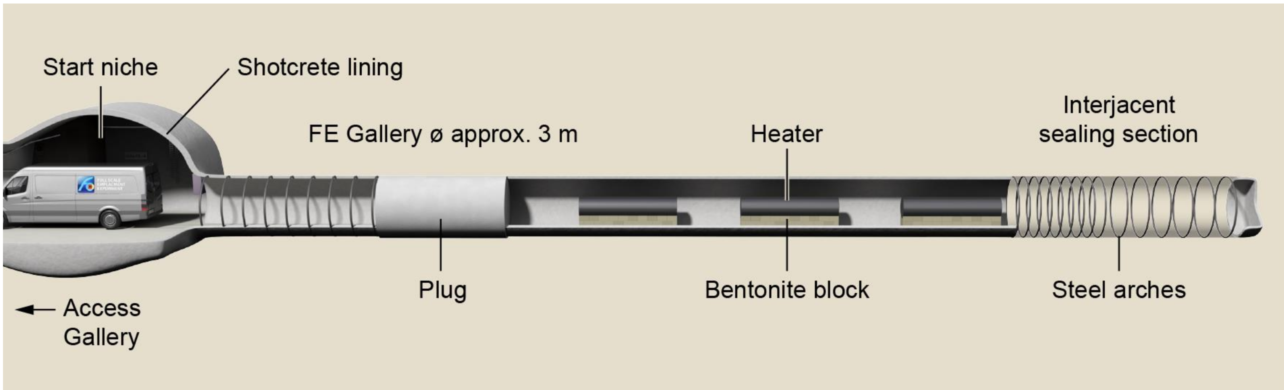

Figure 1: Visualisation of the FE/LUCOEX experiment at the Mont Terri URL representing a section of the repository tunnel (backfill not shown).

1 Granulated bentonite mixture (GBM): design and production steps of a self-compacting material

Blümling & Adams (2008) presented a summary of the work carried out on the use of bentonite pellets as a backfill material as part of the borehole sealing project within the context of the Phase IV (1994 – 1996) research and development activities at the Grimsel Test Site, in collaboration with the Agence Nationale pour la gestion des déchets radioactifs (Andra). The authors showed systematically that the emplacement dry density is dependent on:

- The dry density of individual pellets
- The grain size distribution of the pellets
- The particle shape of the pellets
- The emplacement method

The different issues raised by Blümling & Adams were further investigated in a series of experiments (e.g. Kennedy et al., 2003; Plötze & Weber, 2007).

The design basis for the production of the FE backfill material is discussed based on work by previous authors. Practical lessons from the FE GBM production are then summarised, focusing on:

- The pelletization method and pre-treatment of the raw material required for achieving high quality compaction
- Mixing method for obtaining a broad grain size distribution and hence a self-compacting mixture that will reach a high emplacement density

The production of a bentonite pellet mixture includes several processing steps (Hoffmann et al., 2007). The raw material is generally provided at a gravimetric water content of about 10 – 15 %. It is dried by heating to obtain a lower water content in the range of 3 – 6 %, close to Proctor's optimum, enabling a higher pellet dry density after compaction. The maximum temperature to which the raw bentonite may be exposed during the drying process was determined for this project to be 80 °C. Considering the upper temperature limit of only 80 °C, the efficiency of the drying process depends on the grain size distribution of the raw bentonite material and the residence time in the heating chamber. Maintaining a reasonable production rate of 1.5 tons/hour, the water content of the FE bentonite could be decreased to 4 – 6 %.

The aim during the pelletizing process is to increase the pellet dry density, i.e. to reduce the intra-pellet porosity. For the FE experiment, the pellets were produced by compaction between flat rollers (resulting in flat pellets of irregular shape). Although alternative methods exist (see Pietsch, 2005), this method was found to be favourable from an economical point of view with a reasonable production rate (1 to 2 tons per hour). However with this method the maximum grain size of the pellets was 8 millimetres instead of 15 millimetre diameter that was targeted. The pellet shape was elongated.

The bentonite pellets produced were then mixed in a Kniele mixer, providing enough energy input to break some of the pellets and produce a mixture with broad grain size distribution with the aim of reducing the inter-pellet porosity by filling larger pores between large particles with smaller particles at all scales between zero and the maximum grain size. A specific mixing cycle, including high energy mixing of pellets only in the first phase and smooth mixing after addition of 20 % of raw material in a second phase, was designed to obtain a grain size distribution close to a Fuller type distribution (illustrated in

Figure 2; Fuller & Thompson, 1907). The mixture production rate was approximately 2 tons/hour.

Figure 2: Photo of the granulated bentonite mixture (GBM) produced for the FE experiment.

Intensive testing of the pelletizing and mixing processes resulted in 4 main mixture types. The influence of pellet dry density and grain size distribution are illustrated in Figure 3 where the pouring dry density of the 4 different mixtures is compared. As the mixture density depends on the measurement method, a measurement protocol was designed to compare the mixture dry density during production. Nevertheless, the presented values should not been interpreted in absolute terms. The FE tunnel was filled exclusively with mixture 3 (heated section) and mixture 1 (interjacent sealing section and section close to plug).

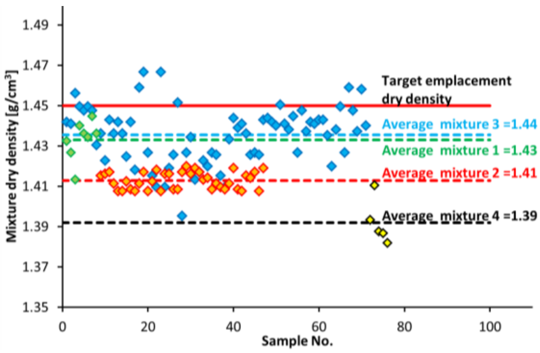

Figure 3: Comparison of the pouring dry density for FE mixture 1 (green dots), 2 (red dots), 3 (blue dots) and 4 (yellow dots), measured every 2 tons during production.
Mixtures 1 and 3 are characterised by a similar grain size distribution and a similar pellet dry density. Mixtures 3 and 4 are characterised by a similar grain size distribution but the pellet dry density of mixture 3 is approx. 10 % higher than that of mixture 4. Mixtures 1 and 2 are characterised by a similar pellet dry density but mixture 2 is lacking a small amount of fine material and thus deviates from the optimum Fuller curve.

Some of the pellets disintegrate during the mixing process, which results in a loss of pellet dry density. This loss was confirmed by measuring the pellet dry density of different size classes sieved out of the granulated bentonite mixture (Figure 4). Apparently large particles do not suffer density degradation, whereas smaller pellets (that were obtained as a result of splitting larger particles) have a pellet dry density loss of approx. 10 %.

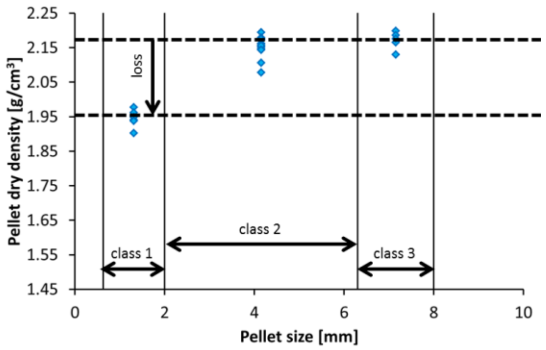

Figure 4: Pellet dry density measured on material sieved out from mixture 3 at ETH using a GeoPyc for three different sizes of pellets (1: between 0.63 mm and 2 mm; 2: between 2 mm and 6.3 mm and 3: between 6.3 mm and 8 mm).
10 measurements for class 1 and 2 and 5 measurements for class 3.

The production of the GBM in four process steps resulted in a satisfactory end-product. A clear and simple recipe (Mixture 3) was designed for a GBM at industrial scale that lead to an emplacement dry density of approx. 1.5 g/cm^3 in the FE tunnel. Potential for further compaction was identified. The material is also robust in terms of storage and handling steps. The initial requirements had to be slightly modified for practical reasons during production (maximum grain size of the pellets was smaller than desired and the mixture characteristics had to be optimised; final mixture characteristics were within requirements). The procedure was defined on the basis of an extended analysis of existing literature. The main control parameters (water content, pellet dry density, grain size distribution of the mixture) were shown to have a low variation, favouring homogeneous emplacement.

2 Compacted bentonite blocks: design and production steps for a highly compacted robust material

A total number of 3000 blocks was required to install 3 block pedestals for the heaters and to backfill 2 metres of the FE experiment tunnel (block mass was approx. 25 kg).

For the FE block production, the recommendations made in SKB (2010) summarising the efforts made since the first industrial production (Johannesson, 1999) were followed. According to previous bentonite block productions, the quality and strength of bentonite blocks depends on:

- (i) The compaction method (isotropic/isostatic or oedometric/uniaxial compression)
- (ii) The compaction pressure, pressing time and pressing cycle
- (iii) The initial water content of the raw material
- (iv) The grain size distribution of the raw material
- (v) The type (mineralogy) of the raw material (Na or Ca bentonite)

Two pre-productions were performed to investigate issues related to items ii, iii and v. The sensitivity of compacted bentonite blocks to ambient relative humidity was investigated thoroughly and systematically to optimise the manufacturing parameters (items ii and iii) and to avoid damage to the blocks during in-situ emplacement operations (Garitte et al., 2015).

Four groups of two blocks with different initial conditions were emplaced at the Grimsel Test Site (GTS) and monitored via a dedicated webcam observation system. The experiment was installed on 19.09.2013 (RH at that time = 70 %). The blocks were loaded with pressure induced by a heater on the bentonite blocks in the FE experiment.

The test was set up to verify previous laboratory test results and to investigate phenomenologically the mechanisms behind those results. Blocks compacted at a low water content disintegrated very quickly, the support capability was lost within only one month and the first significant fractures appeared in the first days after emplacement (Figure 5). Video cameras placed in front of the blocks and recording a picture every minute allowed monitoring the block disintegration behaviour.

In the low water content blocks, the first fractures appeared within the first hours. The videos (see QR codes in Figure 5) clearly showed the link between fracture development and swelling behaviour. The swelling, caused by water absorption by the relatively dry bentonite from relatively wet air, generated cracks that propagated very quickly. The relatively wet air penetrates into the fractures and expands the fracture inside the block. Drying cracks were also observed in the blocks equilibrated at 35 % air humidity (RH) in the laboratory tests, but these were shrinkage cracks and did not penetrate into the blocks. Blocks produced at a higher water content and thus characterised by a higher equilibrium RH took up almost no water and proved to be very stable over a long time period of approx. 1.5 years.

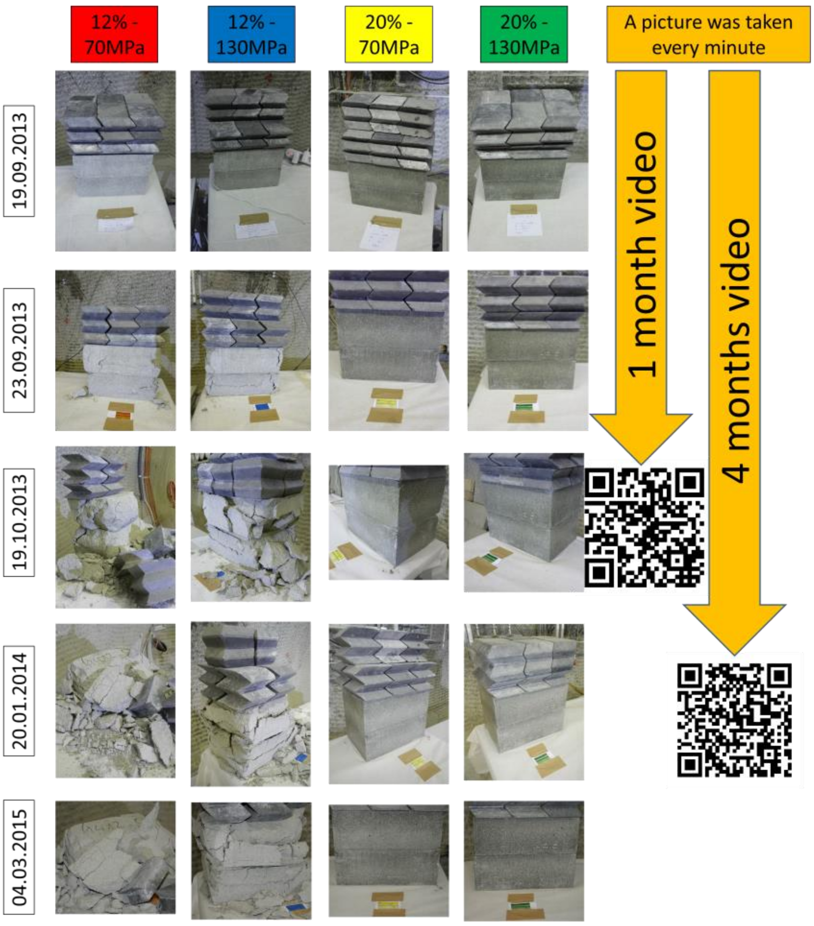

Figure 5: Behaviour of compacted bentonite blocks exposed to a relative humidity varying between 60 % and 85 % for different production parameters (water content and compaction pressure are indicated at the top of the figure).
The QR codes are linked to time-lapse videos of the block evolution.

For the FE bentonite block production, an average block dry density of 1.78 g/cm^3 was achieved. All other requirements, selected according to the state of the art and the pre-tests performed in the FE experiment (geometry variable, strength, density and water content), were checked for each block during production and were found to be fulfilled and very stable over the production time (Figure 6).

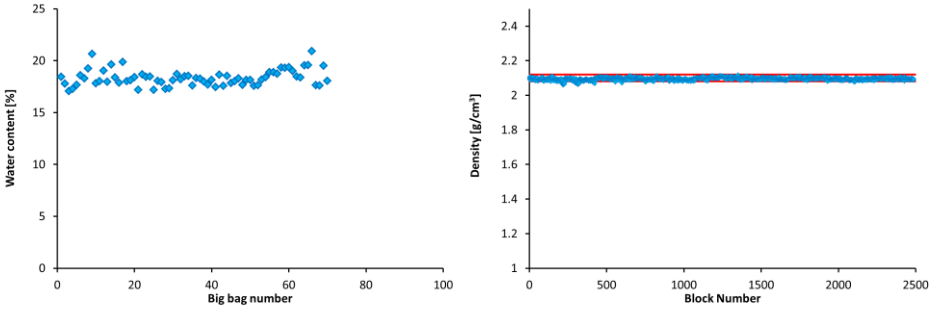

Figure 6: Water content of the raw material after homogeneous wetting (left figure) and block density measured on every block during the production (right figure).

The achieved dry density is a result of the adjustment of the water content of the raw bentonite material and of the compaction pressure to produce bentonite blocks that are as stable as possible with respect to changing climatic conditions in the emplacement tunnel. A higher dry density is possible, but with a loss of resistance to climatic conditions as a consequence. Each compacted bentonite is characterized by an equilibrium RH. Its value depends on the water content and the compaction pressure. A bentonite block is stable as long as ambient air relative humidity does not exceed its equilibrium relative humidity by more than 5 % to 10 %. With the equilibrium RH concept in mind and taking extreme care with packaging, the experience acquired in the FE experiment shows that it is possible to store compacted bentonite blocks for a full year (or longer) without compromising key requirements. Nevertheless, the tests suggested that it might be impossible to produce blocks with an equilibrium RH higher than 70 %. If the ambient RH at the repository site is higher than 80 %, this might result in practical problems during the emplacement activities, but there are technical possibilities for drying the air in the emplacement tunnel.

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