Design and Emplacement of Bentonite Barriers

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Abstract

An industrial production process for high compacted Bentonite materials with low initial water content was developed. Bentonite blocks for drift sealing elements and compacts / granules for bulk mixtures for shaft sealing elements have been successfully tested in large scale in situ tests in salt mines. Since 1998 approximately 500 t of Bentonite blocks have been produced by the company Preiss-Daimler Industries GmbH – Feuerfestwerke Wetro, Germany. The recent shaft sealing systems consist of a binary mixture of dry compacted Bentonite briquettes and granules. Both components are now produced at the plant "Bergmannssegen-Hugo" (K+S Group). Since 2004 approximately 3000 t of this mixture has been supplied.

1 Bentonite under Salt Conditions

The engineered barriers in disposal concepts for radioactive waste consists commonly of Bentonite as a well known sealing and buffer material for hard rock conditions. Underground disposals for chemical toxic wastes are located in Germany in rock salt. Rock salt is one of the potential host rock formations for underground waste disposals for radioactive waste in Germany. Liquid sealed shaft sealing systems in rock salt are required for these applications. Special drift sealing systems in rock salt are also recommended for some cases, for example to isolate mine areas from each other, in order to obtain a higher safety level.

Clay sealing elements for shafts are well known in German classic salt mining and in underground gas storage facilities in rock salt. The implementation of long term stability was impossible, because the database for clay parameters in contact with saturated salt solutions was very incomplete. After singular works (Sitz, 1982) under the support of the Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung - BMBF) research activities were started for measurements of practical relevant clay parameters and for the selection of clays for long term sealing elements under rock salt conditions. The aim of the research is long term stable sealing systems for underground waste disposals in rock salt.

Measurements of clay parameters are carried out in laboratory experiments. Furthermore, the sealing performance of the clay materials was tested in special technical devices under real pressures with salt brine. Such semi-technical tests can demonstrate the complex interaction of real material behaviour, while laboratory tests are limited to the effects of single parameters.

As the final step of the study the feasibility and efficiency of the sealing systems were demonstrated in two large scale in situ tests. Bentonite sealing elements for long term stable shaft sealing systems were tested in the Salzdeturth salt mine with the support of the K+S Group and the Federal Ministry for Education and Research (BMBF) contract 02C0516 from August 1996 to September 2002 (Sitz, Gruner, Rumphorst, 2003) The second large scale experiment, the test of a Bentonite drift sealing construction, was performed in the Sondershausen salt mine with the support of the Federal Ministry for Education and Research (BMBF) contract 02C0547 from October 1997 to March 2003 (Sitz, Koch, Gruner, 2002) and with the co-financing of the Federal State of Thuringia.

1.1 Hydraulic conductivity and swelling pressure

Additionally, to this research, other groups are carrying out similar tests in this area of Bentonite behaviour in contact with high concentrated salt solutions (for example (Daeman & Ran, 1996), (Karnland, 1997), (Dixon, 2000), (Herbert & Moog, 2002)). Some questions of detail in this field of activity are, as yet, ongoing.

The sealing performance of clay is determined by the hydraulic conductivity and by the swelling pressure. The main requirements for the sealing performance are a hydraulic conductivity of $< 5 \cdot 10^{-10}$ m/s (for liquid tightness of the sealing element) and a swelling pressure of approximately 1 MPa (for the tightness in the contact zone between the sealing element and the rock contour).

Both parameters are dependent on the type of test solution, the type of clay and the dry density of the clay. For the rock salt condition the test solution must be a saturated NaCl-solution. For this application it is reasonable to test commercially available clays and Bentonites by various dry densities. As a result of these measurements a natural calcium Bentonite ("Calcigel") has been selected as the reference sealing material (Ehrhardt, 2001), (Wagner, 2005) (see **Figure 1).**

Under salt conditions the hydraulic conductivity is higher and the swelling pressure is lower than under freshwater conditions at the same Bentonite dry density. Results from measurements with fresh water or low concentrated solutions cannot be transferred to the rock salt conditions.

It is problematical that single parameters are not transferable to other systems. The hydraulic conductivity and the swelling pressure must be measured for each Bentonite with each solution. These sealing parameters must be controlled during the assembly of the sealing elements.

1.2 Long term stability

The long term stability of clays under saline conditions can be predicted by Natural Analogues – by natural salt clays of the German Permian limestone period (Zechstein). Important Natural Analogues for a Bentonite sealing element in a saline environment are the clay-formations in salt deposits – the brown-red salt clay in the Werra-district and the red salt clay of the Aller-series. After the inflow of salt brines to the Bentonite sealing element, a chlorite-illite mixed layer clay will be finally formed, as it can be found in the natural salt clays (Gruner et al., 2003). Salt clays separate water bearing horizons from potash or salt layers for million of years. Only man-made influences and tectonic events caused limited failures of these layers (Elert & Peter, 1988).

However, new experimental results concerning Montmorillonite alteration in saline solutions (Herbert et al., 2002), (Kasbohm & Herbert, 2007) demonstrate that the kinetics of alteration of Bentonites may be different and that this question requires further discussion.

1.3 Implication for sealing systems in rock salt

Having analysed the results of the laboratory experiments it is recommended that each Bentonite requires a dry density. **Figure 1** illustrates that the required swelling pressure 1 MPa demands a higher dry density, as the required hydraulic conductivity $< 5 \cdot 10^{-10}$ m/s. To attain this value of swelling pressure in contact with salt solutions, the initial saturation of the Bentonite with water must be as small as possible. So a minimum of initial moisture content of the Bentonite is required. In practice an initial Bentonite moisture content of 10 % is possible.

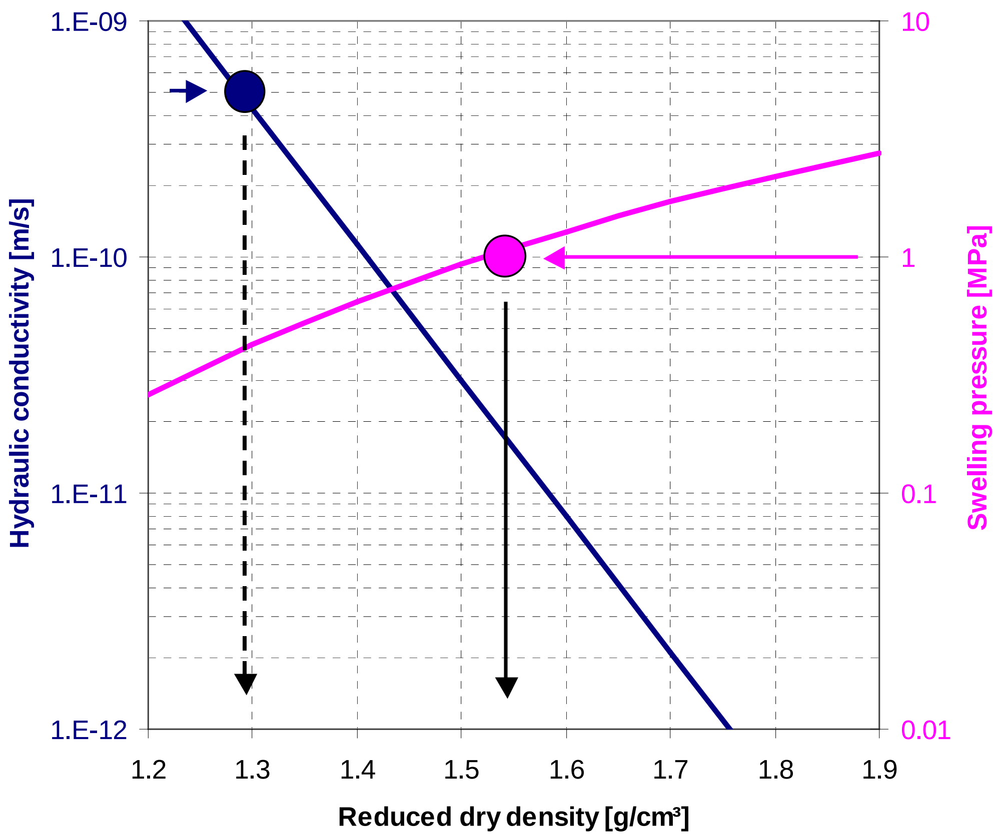

Figure 1: Hydraulic conductivity and swelling pressure of Cacigel Bentonite with NaCl-brine as a function of the reduced dry density of the Bentonite according to data of (Wagner, 2005).

The emplacement dry density is also a function of the potential volumetric deformation of the Bentonite:

$$\rho_{tr} = (1 + \varepsilon_V) \cdot \rho_{red}$$

ρ_{tr}	Bentonite emplacement dry density [kg/m³],
ρ_{red}	Reduced dry density of Bentonite [g/cm³],
ε_v	Volumetric deformation (ΔV/V) [-].

For this reason the emplacement dry density of Bentonite is correspondingly higher. For example, the required emplacement dry density for the reference Bentonite Calcigel is > 1.6 g/cm³ if the volumetric deformation is 5 %. With the same conditions the emplacement dry density of swelling clays with lower Montmorillonite content should be > 1.8 g/cm³.

With such a dry density there needs to be at the same time a low initial water content (< 10 %) calls for a industrial compaction process for Bentonite. High compacted Bentonite materials with low initial water content may be blocks or compacts with different sizes (granulate and briquettes).

2 Shaft Sealing Elements

Bentonite materials for shaft sealing elements under ideal conditions must be a free flow bulk material, which can be (after emplacement in situ) compacted to the finish dry density. Such bulk mixtures can be multi-component mixtures, for example granulates with a Fuller-distribution of the grain size, or binary mixtures. In the comparison of these two different mixtures the later was selected and the Fuller was not, because the high emplacement density can be attained with only two components. This fact makes the production process and the quality control easier.

2.1 Binary bentonite mixture

A continuous compaction process was developed for the Bentonite MX-80 (Naundorf & Wollenberg, 1992) and then adapted to Ca-Bentonite. Bentonite compacts are formed on a roller press compactor by cold briquetting process without adding water or binder. The main product is cushion shaped briquettes with a dry density of up to 2.1 g/cm³ and a water content of 8 – 10 %. Granulates are produced by controlled crushing of the compacted briquettes in a hammer mill (See **Figure 1**).

Figure 1: Bentonite compacts (briquettes, granulates) and binary Bentonite mixture after dismantling.

The optimal configuration of the binary mixture is 70 mass % briquettes (each volume 10 cm³) + 30 mass % granulate with a size of 0 – 3 mm. With this mixture under real in situ conditions an emplacement dry density of 1.70 – 1.75 g/cm³ was realised.

It was indicated in the laboratory and technical tests that commercial borehole pellets or final drying clay granulates, such as cat litter, are not suitable as sealing materials for saline conditions, because the initial water content is too high and the dry density too low (Ehrhardt, 2001).

2.2 Salzdetfurth in situ test

The binary bentonite mixture was tested in situ in a drilled shaft (diameter 2.5 m) in the Salzdetfurth salt mine (See **Figure 2**).

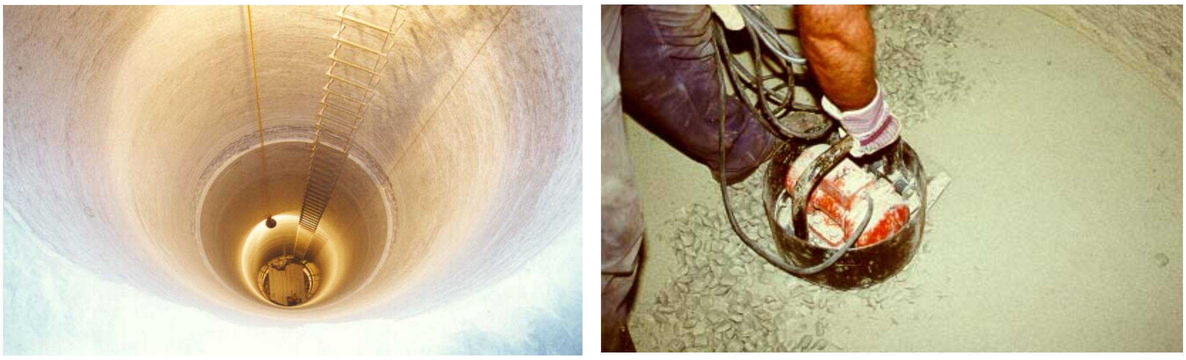

Figure 2: In situ test in Salzdetfurth salt mine, shaft contour (left), emplacement of bentonite (right).

The project was managed by K+S and with the participation of the Institute of Mining Engineering (TU Bergakademie Freiberg), DBE, GRS, IfG Leipzig. The final test of the bentonite sealing system was carried out by constant fluid pressure test phases of 4 MPa and 7 MPa. **Figure 3** demonstrates that the volume flow into the bentonite is decreasing with time. Unsteady infiltration rates are also decreasing with time and with increasing fluid pressure (measured rates $5.8 \cdot 10^{-11}$ m/s at 4 MPa pressure and $4.4 \cdot 10^{-11}$ m/s at 7 MPa pressure).

The in situ test in the Salzdetfurth salt mine demonstrated the suitability of the designed bentonite sealing material (binary mixture of briquettes and granulates) and of the developed emplacement technology for the sealing performance under saline conditions, at high pressures of saturated NaCl-solutions.

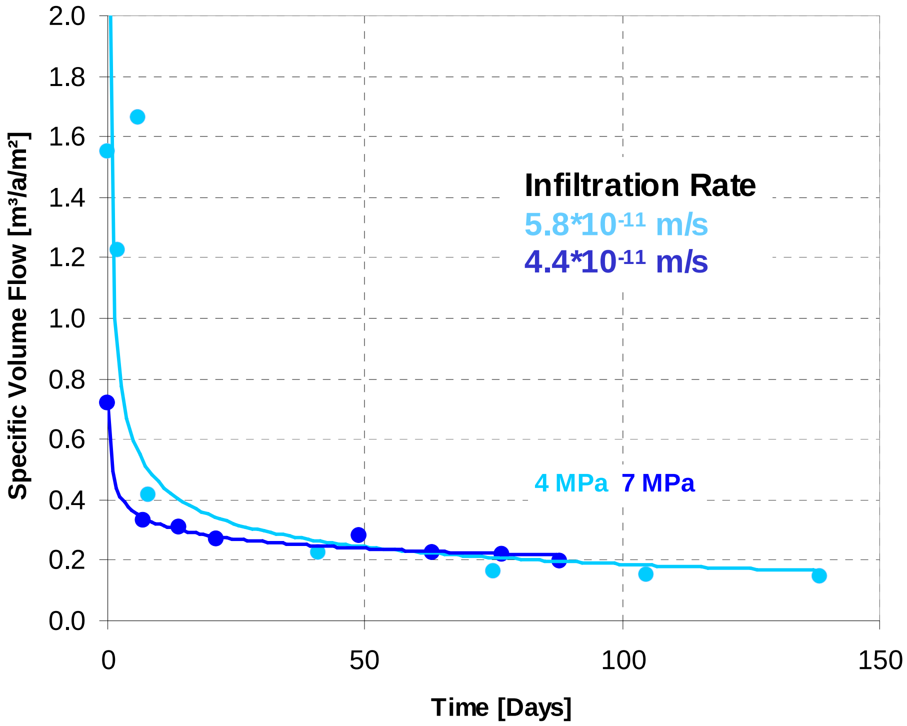

Figure 3. In situ test shaft sealing elements – sealing performance.

2.3 Advanced shaft sealing concept

The positive results of the Salzdetfurth in situ test induced the development of an advanced shaft sealing concept for salt mines on the basis of the Salzdetfurth-type of bentonite sealing system. Both components of the Bentonite mixture (briquettes and granulates) are now produced at the plant "Bergmannssegen-Hugo" by the K+S Group. This material defines the actual best state of the art for bentonite sealing materials for long term stable shaft sealing systems, especially under difficult conditions such as in salt mines.

Since 2004 approximately 3000 t of bentonite briquettes and high quality granules have been produced. For this reason three shaft sealing systems for the final closure of the Salzdetfurth mine were realised. Under the responsibility of the K+S Group eight shaft sealing systems are intended to be constructed before 2015 (closure of the salt mine "Merkers"). Furthermore, the Salzdetfurth-type shaft sealing concept is under discussion for the shaft sealing systems of the Morsleben repository (ERAM) and the Asse test site.

3 Drift Sealing Elements

Bentonite brickwork is most suitable as a sealing element in horizontal openings. Bentonite materials for drift sealing elements can also be a free flowing bulk material, if the in situ compaction to the required dry density is possible.

3.1 Production of bentonite blocks

Blocks of pure bentonite are produced with moisture contents in the range from 14 to 16 %. This moisture content is too high for using under saline conditions, because a high moisture content involves a high initial degree of saturation with water and thereby a lower swelling pressure in successive contacts with salt solutions. These negative aspects can be prevented, if special classified sands are added to the bentonite, whereby the rate of additional water can be significantly reduced. The sand added to the bentonite increases the stiffness and reduces the shrinking of the blocks. Other additives or binders are unfavourable. Effective bentonite dry densities of 1.7 g/cm³ already can be attained with bentonite contents in the range 35 - 55 % and block dry densities up to 2.0 – 2.2 g/cm³.

One question is the optimisation of the block size under specified production conditions. Small sized blocks require lower press capacity and therefore involve less attrition of the tools, are simple in handling and are less damageable during handling under rough underground conditions.

Such kinds of blocks were developed by the Institute of Mining Engineering (TU Bergakademie Freiberg) in cooperation with the Preiss-Daimler Industries GmbH – Feuerfestwerke Wetro. Since 1998 some 500 t of Ca-bentonite blocks have been produced and assembled in underground sealing elements in salt mines. The blocks have a bentonite content of 30 %, 50 % or 60 % and a standard size of (250 x 125 x 62.5) mm. For transportation purposes 206 blocks were assembled on each pallet to a height of 600 mm.

3.2 Emplacement and implementation

The emplacement of bentonite blocks should be done as dry brickwork (See **Figure 1**). A proper fit of the sealing element to the surrounding rock contour can be easily formed by dry sawing. This technology was developed for the in situ test in the Sondershausen salt mine. The project was managed by the Institute of Mining Engineering (TU Bergakademie Freiberg) with the support of the Sondershausen salt mine (GSES) with the participation of the IfG Leipzig, ERCOSPLAN Erfurth, IBeWa Freiberg. The assembling was operated by TS-Bau, a subdivision of Thyssen-Schachtbau.

The settlement of the block formation was < 0.2 mm after 6 days at a height of 3 m. The average gap between the blocks was 0.034 mm (maximum 0.4 mm horizontal – 0.6 mm vertical), to the rock contour the maximum gap was 1 mm.

The construction was tested to the point of maximum fluid pressure of 8 MPa. In summary, the in situ test of the sealing element demonstrated the feasibility of liquid tight sealing elements with the performed bentonite blocks. The results of the in situ test agree with the basic concept for bentonite drift sealing elements in salt mines for underground waste disposal. With this concept in 1996 a sealing system was planed for a drift between the salt mines of Sondershausen and Immenrode. This construction was finished in 1998. The long term sealing element has a diameter of 3 m and a length of 27 m and was constructed with Bentonite blocks FS70 (30 % bentonite) and FS50 (50% bentonite).

Figure 1: Emplacement of bentonite sealing elements in rock salt.

4 Outlook

For shaft and drift sealing under saline conditions bentonite materials (briquettes, granulates, and blocks) were developed and tested in situ. The wide experience with these materials is very useful for applications as a buffer and a sealing material for radioactive waste disposals. Excepting shaft and drift sealing the described materials are practical for the following objects:

- Binary mixture of bentonite briquettes and granulate could be employed as sealing materials in horizontal openings. For this purpose tests for in situ compaction are necessary. In openings with an uneven surface contour, such bulk material may be more adaptable than blocks. The higher deformability of the binary mixture in comparison with the brickwork of bentonite blocks may be unfavourable.

- Granulate with a size range of 0-3 mm up to 0-10 mm could be used as a sealing or a backfill material. For this purpose application and emplacement tests are necessary.
- Mixtures of bentonite granulate / briquettes with aggregates of sand / gravel involve bentonite contents of up to 24 %. Traditional sand-bentonite-mixtures have a maximum bentonite content of 10 – 12 % and therefore a low effective bentonite dry density. For more efficient sealing performance the bentonite content must be higher. With bentonite powder this is impossible. Mixtures based on bentonite granulate are more favourable in reference to a sufficient stiffness and load capacity, respectively. The composition of these mixtures can be designed against the required hydraulic and mechanical properties.

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