Long-term stable, fluid-tight sealing constructions in saline environment - basic concept, research, planning, construction test

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The basic concept for long-term stable sealing constructions must fulfil the following requirements:

- Division of load distribution and sealing (tightening) function
- Use of natural, long-term stable materials like clay, bentonite, asphalt, natural bricks, salt-blocks
- High, steadily increasing safety level of the sealing system

A number of tests in the laboratory, using pilot scale devices and were carried out at underground testing sites to determine the properties and efficiency of compacted bentonites and asphalt's, in salt, the properties of different natural bricks and the permeability of the excavation affected area. For the proof of the feasibility and efficiency of the testing results a real sealing construction was planned, constructed and tested. The seal was constructed in a depth of 700 m, and had a cross-section of about 12 m^2. It was tested with a fluid pressure (salt-brine) of 80 bar.

1. TASK

Sealings of underground openings are not only necessary in operating mines, but also for a further use of the underground openings for instance for the storage and for the underground disposal of wastes with different endangering potential up to radioactive waste. In vertical openings sealings of limited life time for underground gas storage sites (for instance shaft sealings) proven to be tight for more than 2 decades. For this reason in the following only long-term stable sealing systems with a high safety level for horizontal openings will be introduced. Such sealings will be used - beside others - for the isolation of high toxic waste from the biosphere.

2. REQUIREMENTS FOR THE BASIC CONCEPT

For the basic concept for this long-term stable, fluid-tight sealing system on a high safety level the following preconditions were established:

- The location is situated in homogeneous, possibly fine crystalline salt, not influenced by tectonic movements or man made influences.
- The sealing function and static function will fullfilled out by two separate, independent acting systems (sealing element, static element).
- For both systems materials will be used, which have proven their long term stability by natural and/or archeological analogues.
- The sealing construction must be maintenance-free, robust, reasonable and installable with a standard procedure.
- The stability and tightness of the entire system including excavation affected area must be given for all possible load cycles, including the time directly after construction independent of the creeping rate and rock pressure.
- The safety potential increases with time. Developing rock pressure, progressing saturation front and increasing swelling pressure in the bentonite seal have a positive influence on the sealing system, the static abutment and the excavation affected area.

If a very high safety level is; required (for instance for the final disposal of high radioactive waste), various elements can be arranged for sealing and static abutment.

The load distribution at the sealing element and the tightning function of the static abutment remain unconsidered in the calculation.

3. RESEARCH REGARDING MATERIAL PROPERTIES AND MATERIAL SELECTION

The discussion will be restricted to following items:

1. The proof of the long-term stability by natural analogues. The term natural analogue describes natural systems were physical and chemical processes occur which are similar to processes which are assumed to occur over long-term periods at the location of the sealing systems.

2. The determination of real material parameters in half-technical testing devices.
3. Tests of the entire sealing system in a salt mine.

3.1. Materials for the sealing system

High compacted bentonites and/or bitumen (or asphalts) can be used as sealing materials. For the assessment of the behavior of clay(bentonite)-salt-systems the resulting material-properties due to the long-term influence of brines are important. Clay layers, in their stable final state, which can be found in salt deposits, can be seen as natural analogues. In this case comparable (primary) raw materials exist and the conditions and the time dependent alterations for natural formed salt-clays and bentonite as sealing element are also comparable. Consequently bentonite fulfils in a saline environment over geological time periods its task, as confirmed by clay-formations in salt deposits (like brown-red salt-clay in the Werra-district or red saltclay of the Aller-series). The long-term stability of bitumen is proofed by historical analogues (buildings in Pompei, at the rivers Euphrat and Tigris, in Egypt), by natural analogues, like the asphalt-sees in Trinidad and on Bermuda, and also by inclusions of salt in bitumen. For the determination of the properties of bentonite in a saline environment extensive tests were carried out:

- to determine the negative influence of salt brines on the properties of bentonite,
- to determine the influence of high pressures (over 100 bars) and high pressure gradients on bentonite.

Beside classical standard tests, new developed testing devices were used. Such devices are for example:

- A pilot scale testing device with 800 and 300 mm diameter respectively up to a length of 2 m and salt-brine pressures up to 250 bars for the determination of the hydraulic conductivity, the compaction behavior, the load distribution and the determination of the swelling pressure.
- The further development of construction layouts for swelling pressure test devices, which were disposed by courtesy of ETH Enrich, Institute of Geotechnics, and the construction of such devices.
- A large oedometer (diameter: appr. 250 mm height: appr. 100 mm, maximal pressure stresses: up to 13 Mama) for the determination of the settlement behaviour of dry bentonite products and for the measurement of the swelling pressure.

Eventually, two bentonite products which can be used underground and which are producible in large scale, were developed in cooperation with industry:

1. Compacted bentonite pellets (dry density > 2000 kg/m^3) as bulk material or for blowing in. It is especially suited for vertical openings and free spaces between rock and built-in material. With binary mixtures bulk densities up to 1350 kg/m3 (dry density) can be established. With a further compaction the density can rise up to 1700 kg/m^3. These pellets have better properties than recently available pellets.
2. Bentonite-bricks with different shapes, which consist of 30 ... 70 % bentonite and a special fine sand. The addition of fine sand has economic advantages and it improves the material properties (high deformation modulus, better handling, good compaction, high friction angle and high coefficient of adhesion). Some guaranteed properties of one selected product are given in table 1. Figure 1 shows the building-in of bentonite bricks in an underground mine.

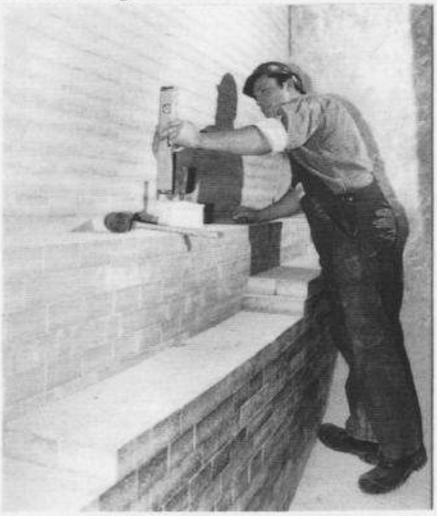

Figure 1. Placing of bentonite bricks

Because of the good experiences with bitumen/asphalt in vertical sealing systems (whereby the density layering supports the sealing effect) laboratory tests and tests in pilot scale for the use of these materials in horizontal openings were carried out. It was found, that poured asphalts of special composition are also suitable for the sealing of horizontal openings. These poured asphalts well suited for high safety requirements in combination with compacted bentonite bricks (diverse safety strategy).

Table 1
Delivery conditions for bentonite bricks (FS 50)

Parameter	Delivery conditions (guaranteed values)	
Density	2,25	(g/cm^3)
Water content	7-10	(%)
Bentonite content	> 50	(mass%)
Dry density of bentonite	1,63-1,72	(g/cm^3)
Compressive strength	8	(MPa)
Young's modulus	2	(Gpa)
Hydraulic conductivity	2. 10^{-11}	(m/s)
Swelling pressure	1,5	(MPa)

3.2. Materials for the static abutment

Bricks, which are formed from hewn native rock and built in dry (without mortar) can be used as construction material for abutments. In the following basalt-rock, natural rock-salt blocks and rock-salt pellets (salt briquettes) are considered (table 2).
The following results were obtained by tests in the laboratory, by tests at the underground testing field (figure 2) and by numerical calculations of the system abutment-rock:
Pelletized rock-salt briquettes have better mechanic properties and are more economic than cut rock-salt bricks.
Basalt is mechanically and chemically more stable than rock-salt briquettes. Since the abutment material acts in combination with the surrounding salt rock, the high stability (strength) of the basalt can be used in limited scale only. Beside this, basalt is very expensive.

Table 2
Properties of building materials for the static abutment

Properties	Basalt	Rock salt	Salt briquettes
Young's modulus (GPa)	50-100	15-30	18-30
Density (g/cm^3)	2,8-3,2	2,1-2,2	2,17
Porosity (%)	0,1-4,5	0,3-6,5	8-9
Tensile bond strength (MPa)	14 - 65		1 – 1,5
Tensile strength (MPa)	10 – 35	0,2–3,0	
Friction angle (^{0})	40 - 60	50 - 60	45 - 50
Permeability (m^2)		10^{-21} – 10^{-23}	10^{-16}
Compressive strength (MPa)	110-400	10-40	45-60

Because cheaper rock-salt briquettes fulfil all requirements, this material was used for tests and for the test-dam in the underground salt mine. Because of the small tolerances and the creeping behavior of rock-salt briquettes, the abutment can be seen as "real built-in dry", i.e. without sand or salt for the filling of the joints.

3.3. Excavation affected area

Native salt layers (primary stress state) have permeabilities of < 10^{-23} m^2, i.e. these layers are impermeable. Due to the construction of openings, the permeability of the surrounded rock (excavation affected area) increases. This must be considered in the planning and calculation of a sealing system. The measurement of the permeability was done with a procedure, developed by the Institute of Drilling and Fluid-Mining of TUB Bergakademie Freiberg. It is possible to measure permeabilities up to 10-14 nil in pressurized bore-holes, starting 6 cm apart from the free face. Figure 3 shows the permeabilities in the side wall of an opening driven 35 years ago by a

TBM with a diameter of 3 m. The permeabilities of the rock, determined in this way are the basis for an additional break-out and additional procedures a (sealing slots) as well as the selection of the material and the length of the sealing element.

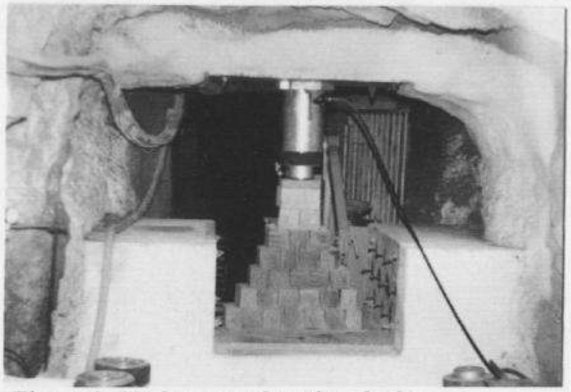

Figure 2. Underground testing device

4. PRINCIPLES FOR CALCULATION AND PLANNING

The calculation of the static abutments is done with numerical program-systems like FLAC or

ABAQUS. The calculations have shown, that static abutments in the shape of a truncated cone or a prismatoid, a having a length comparablt to the diameter, made from hewed native basalt or rock salt briquettes with inclination-angles of 120 to 160 and fine sand or fine salt respectively for the filling of the free space at the contact zone have a sufficient safety level against all possible load states (fluid pressure, rock-pressure) at a depth of 700 m.

The objectives of the calculation for the sealing element are length an the quality of the bentonite, i.e. the kind of bentonite and dry density of the dry built in bentonite. These parameters determine the hydraulic conductivity and the swelling pressure. The calculation is done on basis of an allowed total volume flow (for instance in the magnitude of the evaporation rate), which consists of the volume flows through the sealing material, through the contact plane and through the excavation affected area. The volume flow through the contact plane is reduced - beside others - by swelling pressures, a special treatment of the joints and a partly wedge shaped construction of the sealing element. The volume flow through the excavation. affected area will be reduced by the removal of loosened rocks and additional measures, like sealing slots. Figure 4 shows a horizontal sealing system for pressures from one side which fulfils maximum requirements. It

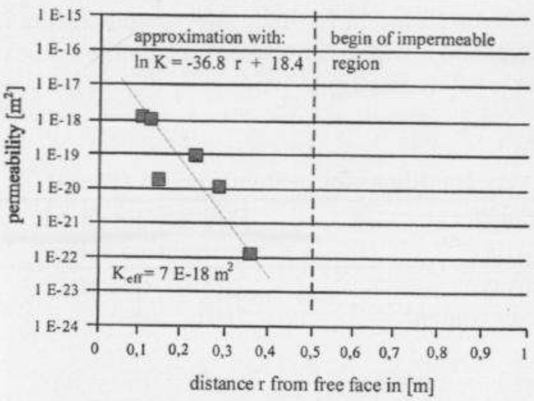

Figure 3. Measured Permeability in a horizontal Test-Hole at the South-West Face

consists of various elements for load distribution (static abutment, following backfill) and for the sealing (bentonite bricks, poured asphalt), which can be left, if the requirements are not that strict. Amongst others the following principles were consider ed: dry built-in of the bentonite, saturation of the incoming salt brine, no joints over the full length parallel to the drift, fissure-free deformation of the sealing material under rock pressure.

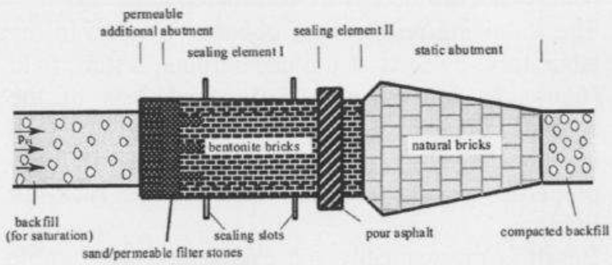

Figure 4. Basic layout of a long term stable drift construction with fluid pressure from one side

Beginning at the pressure side, the system consists of the following elements:

1. Backfill with material for the saturation of incoming brines and for the stabilization of the rock.

2. Permeable additional static abutment for the reception of the swelling pressure (natural bricks, long-term stable filterstones).
3. Filter-layer for an evenly action of the fluid pressure on the sealing element (sands and/or permeable filter-stones).
4. Sealing element I (compacted bentonite bricks).
5. Sealing slots, filled with low permeable material (Reduction of the circulation of brines through the excavation affected area).
6. Sealing element II (a special pour-asphalt in combination with bitumen and following bentonite bricks).
7. Static abutment, for the reception of the fluid pressure and rock pressure (native basalt or rock-salt bricks or rock-salt briquettes).
8. Compacted backfill, for additional load distribution (gravel).

5. UNDERGROUND PRETESTS AND TEST SEALING CONSTRUCTION

The function of a long-term stable drift-sealing construction will be proven by underground in-situ. tests in a depth of 700 m in a salt mine in two steps:

1. Pre-test sealing construction.

Pre-test in an opening with a volume of 1 x 1 x 2.5 m^3 , worked out by drilling and subsequent smoothing of the contour with the following objectives:

- The confirmation of the results from tests in the laboratory and the pilot scale testing device,
- The test of the construction techniques including the bottom-canal for the pressure load, the pressure load by the membrane-pumps, the function of the pressure chamber, the measuring equipment and the data transfer,
- The test of the tightening behavior of the sealing element, of the contact zone and of the excavation effected area as well as the load distribution of the static abutment.

The basic concept and the feasibility were proven by these pre-tests with fluid pressures up to 30 bars. Some findings were included in the basic concept and the test sealing construction. Examples are measures for the improvement of the sealing of the contact plane, like the establishment of a smooth surface with rope-saws, the use of a special bentonite-granulate for the filling of the free space at the contact plane, the slightly wedge shaped formation of the roof at the pressure side, the concentric placement of filter-stones at the fluid pressure side over a limited area. By measurements of the wetness at core-samples (radial boreholes in the rock) the flow around the sealing through the rock could be proven.

2. Large-scale test of a sealing construction.

The sealing system in the scale 1 : 1 has been recently tested (fluid-pressures up to 80 bars). The system has been constructed in a drift with a diameter of 3 m, driven 35 years ago by a TBM. With the help of a rope-saw the cross-section was extended to a rectangular shape with a surface of 3.50 X 3.20 m^2. With this final test the basic concept is proven regarding its function and the fulfilment of all requirements. The function of the sealing element, of the abutment and of the entire system will be registered by measurements of the load, the location of the saturation front, the swelling pressure, the volume flows, the load distribution/stress state and the displacements as well as the registration of the influenced zone in the rock with passive and active acoustic procedures and over radial bore-holes.

6. LITERATURE

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