Drift Seals at the Asse II Salt Mine – A Summary of more than a Decade of Experience – 21107

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ABSTRACT

After the end of rock salt and potash salt extraction in the Asse II mine located in Northern Germany low- and medium-level radioactive waste was emplaced. The waste volume was around 47,000 m³ and the work was carried out from 1967 to 1978. The occurrence of solution inflows and the difficulty of predicting their progression led to the decision of the waste retrieval. The Law on Speeding up the Retrieval of Radioactive Waste and the Decommissioning of the Asse II Mine (Lex Asse) became effective on 24 April 2013. Sodium chloride solutions can severely damage support elements of the mine structure. Therefore, high inflow volumes, that cannot be removed, would require a counter-flooding of the mine voids with inert magnesium chloride solution. In this case, seals or so-called flow barriers should control the flow of the solution and protect the emplacement chambers. To ensure this function, the barriers should exclude pore or crack systems, which would enable any flow of solution. Hence, a low-permeable sealing material is required as well as a suitable barrier design with a sufficient resistance against all stresses, occurring during their life cycle. In order to prove the integrity and functionality of the barriers, a modular concept was developed. The concept is structured in individual safety proofs according to the actions that can affect the barriers. The aim of each proof is to clearly demonstrate that the barriers withstand the actions with the necessary safety margin. The concept developed can be adjusted for varying materials, locations, host rock and other requirements. An example is the addition of a module proving the thermal stability in case of a barrier construction in repositories with heat-generating waste.

For the construction of flow barriers a magnesia binder was developed called ‘Sorel concrete A1’. A crack-free hardening of the concrete is guaranteed through the built-up of a pressure regime by the swelling of the given recipe when poured between massive abutments. A low compaction of the concrete in the hardened state in combination with the rock convergence leads to a pressure built up that prevents bypassing of fluids. Due to the high strength and the excellent bond strength of the concrete the rock mechanical loads cannot cause any damage and barrier integrity is ensured. Changes in the material properties, i.e. corrosion of the Sorel concrete, are not possible, thus the long-term stability of the barriers is also proven.

The flow barriers at Asse II have been built since 2007 according to a detailed quality assurance plan. All findings and the structural proofs for each barrier are summarized in a document including technical feasibility. By now, more than 50,000 m³ of concrete have been used for the construction of around 40 flow barriers including the full-scale pilot barriers constructed for confirming the feasibility of the construction. According to the proven concept, about 40 more flow barriers will be built until the protective measure will be successfully completed.

INTRODUCTION

The most widespread evaporite deposits in Central Europe originate from the Zechstein era about 250 million years ago. After the sedimentation of a thick overburden, high pressure caused salt to rise upwards. The salt was folded and salt domes with complicated structures were formed [1]. Since the beginning of the 20th century pure rock salt and potash salt were extracted at the Asse II mine in Lower Saxony, Germany. After the salt mining stopped, radioactive waste was emplaced into the mine. In addition to shafts, the mining activities resulted in a network of drifts, chambers, and blind shafts. The high extent of excavation, large and unfilled voids, and the decades of usage caused a great extent of deformation in the rock resulting in a loss of stability in areas close to the waste chambers.

Cracks formed which enabled saline solutions to enter the mine. Currently these solutions are collected and pumped out of the mine, however, an increase of the flow rate cannot be ruled out. As a consequence, the retrieval of the waste has been a statutory order since 2013. Extensive backfilling measures are undertaken in order to stabilise the mine structures allowing safe retrieval operations [2], [3]. However, the contact of potash salts with the entering sodium chloride dominated solutions would destabilize the mine and create flow paths. Consequently, it is planned to flood the mine in the case of a "beyond-design event" with a concentrated magnesium chloride solution. In order to protect the emplacement chambers, seals are constructed in blind shafts and drifts. These seals are called flow barriers as their main task is the limitation and control of the solution flow.

The planning and construction of the flow barriers required i.e. the specification of a sealing material, the development of a barrier design that can be implemented quickly and easily, and the definition of a quality assurance (QA) program. The program and the findings of studies on full-scale in-situ tests (pilot flow barriers) provides the input data for structural proofs of the required barrier performance. This overview summarises information about the sealing material, the basics of the flow barrier design and their implementation as well as the approach of the safety proofs. Today, we look back to almost 15 years of successful construction of flow barriers at the Asse II mine site.

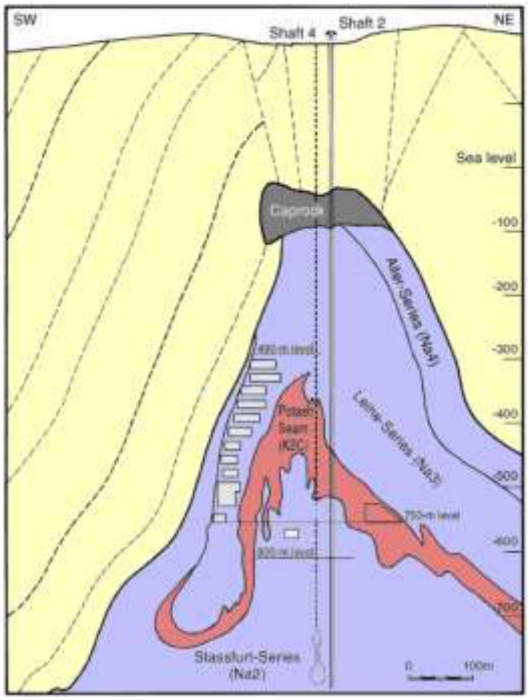

Fig. 1. Geological map of the Asse II salt mine. Rock salt is shown in blue and the potash seam in red.

THE SEALING MATERIAL

The sealing of cavities with a large cross-section, such as drifts or shafts, requires the use of high-quality building materials. Accordingly, material selection is decisive for the success of sealing measures. It is a multi-stage process, which starts with the definition of a set of requirements. This set takes into account all aspects of the application and intended use, such as availability and suitability for storage of the raw materials, and the possibility of the emplacement of the mixture according to the requirements. A low permeability is mandatory for sealing accompanied by suitable mechanical properties that prevent crack formation. However, material properties change when interacting with gases or constituents of solutions.

Therefore, corrosion or material degradation needs to be investigated that could cause an unwanted increase in permeability or decrease in strength.
Additional requirements must be specified for the possibility of reactions with the host rock, which could impair the bond strength and tightness of contact zones. In this regard, the dissolution of salts with high contents of crystallisation water, such as in potash seams, is particularly critical. Thus, the sealing material must be chemically compatible with the host rock and all materials that could cause chemical interactions.

In the next step, the conformity of characteristic properties of building materials with these requirements is checked. For example, crushed rock salt would be compatible with the chemical environment at the Asse II mine. However, crushed salts have a high permeability after placement and compaction requires a long time period. As a result, salts cannot be used where a short-term sealing effect needs to be achieved. Cement-based materials would react with potash salts and corrode in contact with solutions that contain for example magnesium or sulfate ions [4]. Consequently, magnesia binders were shortlisted [5]. Their hardening is based on the reaction of magnesium oxide (MgO) or hydroxide ($Mg(OH)_2$) with a solution rich in magnesium chloride ($MgCl_2$). In most cases the MgCl2 content of the mixing solution is in the range of 30 to 33 wt.-%. Magnesia binders can be processed in similar ways as cement systems. Due to the negligible solubility of the minerals in the evaporite rocks, adverse reactions of the $MgCl_2$ solutions with magnesia binder can be excluded and chemical compatibility is ensured. An additional, characteristic property of magnesia binders is an increase in volume during hardening and if constrained, the build-up of swelling pressure. This behaviour is a result of the crystallisation pressure induced by the formation of magnesium chloride hydroxides. The hydroxides are named after the molar ratio of the chemical components. The 3-1-8 phase described in Eq. (1) is thermodynamically stable under ambient temperatures. Despite the fact that the swelling pressure is only temporarily effective and recrystallization results in a compacted pore space, it improves the bond strength to the rock as well as the tightness of the contact zones with salt rocks.

$$3\ MgO_{(s)} + MgCl_{2(aq)} + 11\ H_2O_{aq} \rightarrow 3\ Mg(OH)_2 \cdot MgCl_2 \cdot 8\ H_2O \quad (1)$$
$$3\ Mg(OH)_{2(s)} + MgCl_{2(aq)} + 8\ H_2O_{aq} \rightarrow 3\ Mg(OH)_2 \cdot MgCl_2 \cdot 8\ H_2O \quad (2)$$

Eq. (1) also indicates that small amounts of the binder have the ability to bind large amounts of solution in the structure of the magnesium chloride hydroxides. As a result, the pore space saturation of the hardened magnesia binder is low, whereby the possibility of volume expansion during hardening must also be taken into account. The fixation of free salt solution into crystal structures therefore causes a strong self-desiccation of the material matrix (cf. [6]).

Mixtures with MgO are used to build the barriers to ensure hardening in a convenient time frame and to achieve high strength and low permeability. Because MgO can bind more solution compared to $Mg(OH)_2$, these types of magnesia binders have a lower porosity. However, high reaction heat can lead to thermal stress, so that the possibility of cracking must be assessed. Mixtures with aggregates contain less binder and develop less reaction heat. Accordingly, concretes with crushed salt aggregate were favoured meeting the requirements of long-term stability. Taking into account a grain size distribution close to the Fuller curve, standard aggregate grading curves and a preferred crystallisation of the 3-1-8 phase, the composition can be described by this simple three-component system. When freshly mixed, it contains 11.3 wt.-% magnesium oxide, 63.7 wt.-% crushed salt, and 25.0 wt.-% magnesium chloride solution. This recipe was named after Stanislas Sorel, the inventor of the non-hydraulic binder system, Sorel concrete A1 with the letter A indicating the use in the Asse II mine. The recipe can be easily manufactured and pumped through pipelines and boreholes. In the hardened state, the uniaxial compressive strength is around 60 to 70 MPa and the tensile strength around 5 MPa, thus significantly above the value of rock salt and potash salt (carnallitite) in the Asse II mine (cf. [7]). A low level of porosity results in a permeability $< 5 \cdot 10^{-18}$ m². Fig. 2 shows sawed surfaces of test specimens, so that the grain structure can be clearly seen.

Fig. 2. Sorel concrete A1 embedded on the left in reddish rock salt. The maximum grain size of the concrete is about 4 mm. The grains of the aggregate are the irregular, dark areas in the light gray matrix. On the right is a microscope photo that shows the concrete at a higher magnification.

THE BARRIER DESIGN

During the backfilling of a cavity the suspension meanders so that a cone with a slightly inclined surface results. Due to this fact, conical cavities that are shaped with a greater roof incline can be backfilled void-free if the venting takes place via the cone tip. In order to limit the flow of the concrete, formwork is usually used. It withstands the force that arises from the density and height of the filling column. However, hardening of large-volume Sorel concrete A1 structures results in significantly higher forces due to the development of the hydration heat and swelling. Accordingly, massive abutments are constructed in order to limit shear stresses along the core barrier. Since they significantly hinder axial deformations in the drifts, they also improve the bond of the concrete to the rock. Formwork walls are used for the concreting of the abutments, because their smaller volume results in lower stresses. Moreover, only their positional stability needs to be guaranteed so they should be wedge-shaped. The pouring of the concrete should be done in any case from higher levels, because the column present in the borehole exerts a pressure that is advantageous for the bond of the concrete to the rock.

Fig. 3 shows the resulting basic, symmetrical structure of the horizontal flow barriers [2]. The length of the core barrier is always significantly greater than the largest cross-sectional dimension in order to ensure plane strain conditions. The abutments must be dimensioned so that their length corresponds at least to the maximum drift diameter, measured at the front of the barrier. Mine cavities adjacent to a flow barrier are backfilled prior to the flow barrier construction in order to create extra stability of the mine area. The Sorel concrete A1 is also used to build the abutments and as backfill, to ensure an efficient workflow and maximum performance of the barrier.

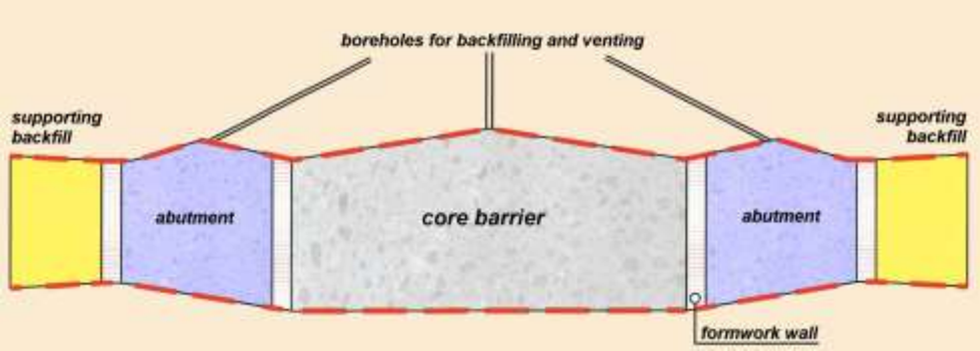

Fig. 3. Section along the axis of a horizontal flow barrier according the basic concept.

The intrinsic permeability of evaporate rocks is exceedingly low. However, excavation of cavities lead to the formation of cracks. They are caused by local stress changes and the mechanical forces that are applied by the technique of exploitation, such as blasting and milling. Due to this fact, there exist a so-called excavation damaged zone (EDZ) at the rock surface, which increases over time. It must be removed as far as possible in order to reach maximum tightness and stability of a barrier.

With the aim of reducing the formation of new cracks and thus creating better stress distributions, the cavity contours are slightly adapted. The "target profile" that is favored due to geomechanical reasons has dome-like shapes at the drift roof and ellipses in cross-section. Sharp edges are always avoided. In the case of an ellipsoidal cross-sections, the maximum ratio of the small to the large semi-axis is 2.8. In individual cases, almost circular or rounded square cross-sections are realized. The ratio of the height and width of the voids is similar to ensure geomechanical comparability of the flow barriers. Experience show that such a simple design can be easily implemented.

The rocks are removed with boom-mounted cutting heads so that a rippled surface is unavoidable. The ripples are arranged in such a way that no air pockets may arise during concreting. In practice it has been shown that, due to deviations in direction, the boreholes have to be drilled first before the drift roof is finally finished. Fig. 4 is intended to give an impression of the implementation of these mining activities. The length of the core barriers extends up to a maximum of around 30 m and the cross-sectional dimensions up to about 7 m, with an average of around 5 m.

Fig. 4. Recutting of the rock salt profile at a site in the Asse II salt mine intended for barrier construction.

THE CONCEPT OF SAFETY PROOFS

During concreting, solution of the suspension penetrates into cracks of the EDZ and concrete composition changes at the surface of the EDZ depending on its roughness, the grain size of the concrete and the flow process. A contour or edge zone with less aggregate develops. As a result, a sequence of different materials exists. It starts with the

- homogeneous core concrete,
- the contour zone with the contact surface on the rock,
- followed by the EDZ, and
- the undamaged host rock,

In order to ensure the barrier tightness, this sequence has to withstand many loads (actions) during and after construction and when sealing against solution. The safety concept considers the sequence from core concrete to the EDZ (cf. [8]). Moreover, the individual modules of the concept take into account the type of action on the structure, whereby a chronological sequence of the occurrence of the actions can also be recognized, and in the case of mechanical loads, differences in the load direction. First of all, a distinction is made between the transient phase or transient design situation and the long-term behavior of the barriers. During the transient phase, thermally induced stresses and volume changes as a result of the hardening of the concrete act. In the long-term, the rock pressure and in case of counter-flooding a solution pressure could act and seismic activities must be taken into account. The solution presses on the face of the barriers, which primarily lead to shear force. Solution that penetrates the EDZ could open cracks, provided that the cracks have not yet healed completely. The barriers must withstand these actions, but their properties could change as a result of reactions with solutions and gases. For this reason, it is also necessary to check whether a chemical attack is effective, i.e. whether the concrete could corrode.

The range of actions and their chronological sequence means that numerous safety proofs have to be provided in order to demonstrate the functionality of the entire structure. Basically it is possible to prove the structural reliability of barriers by calculation or design assisted by testing. In the case of the flow barriers, the results of investigation of so-called pilot barriers were used to carry out the safety proofs of the transient phase. Indicative calculations were performed in order to develop design requirements. The framework conditions for the implementation of the pilot barrier tests were chosen in such a way that transferability of the results to all flow barrier is guaranteed. The execution of the other safety proofs is based on laboratory tests of material properties and numerical calculations using validated modelling tools.

Information on the properties of the barrier, i.e. the barrier resistance and the number and size of the actions are always subject to uncertainties. For this reason, statistical analyzes must always be carried out during the data evaluation and safety factors (partial safety factors) must be defined (Fig. 5). This was done on the basis of the Eurocode family (cf. [9]). The relationship between actions and resistance can also be formulated as safety evidence criteria. Fundamentals for the applicability of the safety factor method to long time periods are described in [10].

Fig. 5. Basis of structural design. In order to demonstrate its function, the resistance of a structure must be greater than the actions, taking into account the uncertainties and safety factors.

If all safety proofs are successful, that is, no situations are possible where actions would exceed the resistance of the barrier system, it is possible to calculate the hydraulic resistance of the barriers taken into consideration the so-called effective length, the effective cross-sectional area, and the integral permeability of the core barrier.

The Transient Phase

During the so-called transient phase, shear stresses occur during heating and cooling of the barrier due to differences in thermal expansion and contraction of its components. In addition, tensile stresses could arise during cooling that exceed material strengths and lead to crack formation. In the case of the flow barriers, these proofs of structural integrity based on the investigation of full-scale in-situ tests, so-called pilot barriers, and computer simulations, which used the results of laboratory tests.

Major attention was given to the temperature and stress development within and around the pilot barriers. The findings clearly show that the abutments sufficiently limit deformation acting in the axial direction and thus the shear forces in the particularly sensitive EDZ and contour zone. However, tensile stresses in the radial direction, which could lead to cracks along the barrier, would be particularly critical. They usually occur during the stage of cooling, especially when building materials were used that shrink during the hardening. Fig. 6 illustrates the relationships over time.

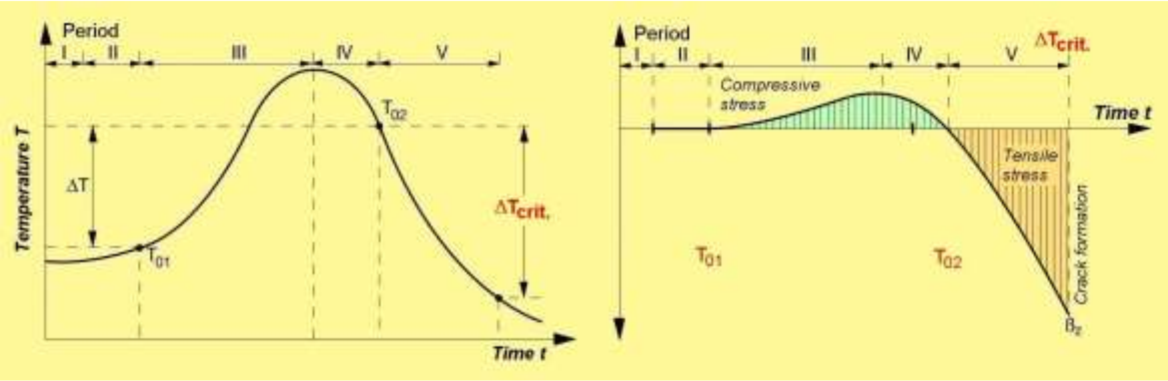

Fig. 6. Development of temperature (left) as well as compressive and tensile stresses (right) in young concrete, which show a so-called autogeneous shrinkage when hardening. Cracks occur when the strength of the material is exceeded as a result of an increase of tensile stresses.

For comparison, Fig. 7 shows analogous data that were registered during hardening of a pilot barrier. The diagram on the left shows in addition to the main peak a temporary temperature rise after around 20 hours. This heat release is based on the conversion of a high temperature phase into the thermodynamically stable 3-1-8 phase (Eq. 1). According to the diagram on the right, there are no tensile stresses that could induce cracks. This positive result also attributed to the swelling of Sorel concrete A1, which compensates thermal contraction.

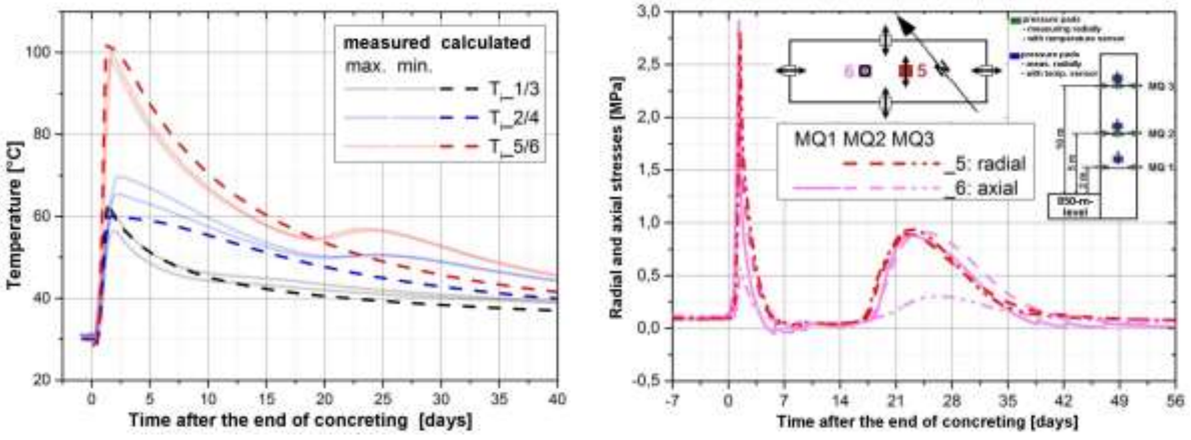

Fig. 7. Pilot barrier test at the Asse II salt mine - Temperature (left) and stress development (right) during the hardening of the core barrier made of Sorel concrete A1. The dashed lines in the diagram on the left are the results of calculations that do not take into account the heat release of the Sorel concrete after around 25 days. Lower temperatures are determined for the edge areas of the barrier and higher temperatures for the core areas.

The long-term barrier function

The investigations of the pilot barriers showed that the barriers are tight and withstand the stresses that have occurred up to now. At the pilot barrier A1, they are about 13 MPa to 14 MPa (radial). With the help of so-called pressure chambers and pressure control devices, the end faces of pilot barriers were loaded with solution and axial stresses of about 2 MPa could be realized. The radial stresses to be expected in the long term are determined for each barrier using numerical calculations. However, in simplified terms they can be roughly estimated by means of Eq. (3), with ρ the average rock density (2,200 kg/m³), g the acceleration of gravity (9.81 m/s²), and D the depth of the barrier below earth surface.

$$\sigma_E = \rho \cdot g \cdot D. \tag{3}$$

For the pilot barrier A1 on the 950-m-level a value of 20.5 MPa results. In analogy, a value of 12.1 MPa represent the expected pressure from a salt solution column with a solution density of 1300 kg/m³. Due to the fact that such high values could not be realized during the in-situ tests additional safety proofs must be provided in order to demonstrate the full function of the barriers in the future. Moreover, this includes the influence of chemical attacks (material corrosion) and seismic activities as additional load cases.

Magnesia binders such as Sorel concrete A1 react with solutions that have a low magnesium chloride content or a high ratio of sulfate and magnesium ions. The possibility of the occurrence of these solutions depends on the presence of potash salts and on the composition of the solution, which is used to flood the remaining cavities in the case of a beyond design event. In larger mine areas, the rock carnallitite is exposed, so that the easily soluble mineral carnallite ($KMgCl_3 \cdot 6H_2O$) dominates alongside bischofite ($MgCl_2 \cdot 6H_2O$). In addition, the solutions selected for the flooding are characterized by high magnesium chloride contents and low sulfate contents, so that degradation of the Sorel concrete A1 can be excluded. This proof of long-term durability had far-reaching consequences for the planning of test series, because solely the dependence of the material properties on the hardening time had to be taken into account and not material degradation.

Comprehensive material tests were carried out under static loading conditions to demonstrate the mechanical resistance of the barriers to radial stresses caused by the rock convergence. Dilatancy and compressive strength are of particular relevance. Here, dilatancy is understood to be the load causing microcracks and an increasing permeability. The results of compressive strengths tests and the extrapolated area with increasing confining pressure are shown in Fig. 8. The points of dilatancy are slightly above the lower dashed line and also rise with the confining pressure. Even when taking into account the uncertainties and safety factors, it can be stated that dilatancy or cracking of the flow barriers is not possible. This statement also applies in the case of the presence of solution, because the solution in mine openings reduces rock convergence, the development of radial stresses over time, and differences of radial and axial stresses. Flooding, for example, also aims to achieve a more favorable stress distribution.

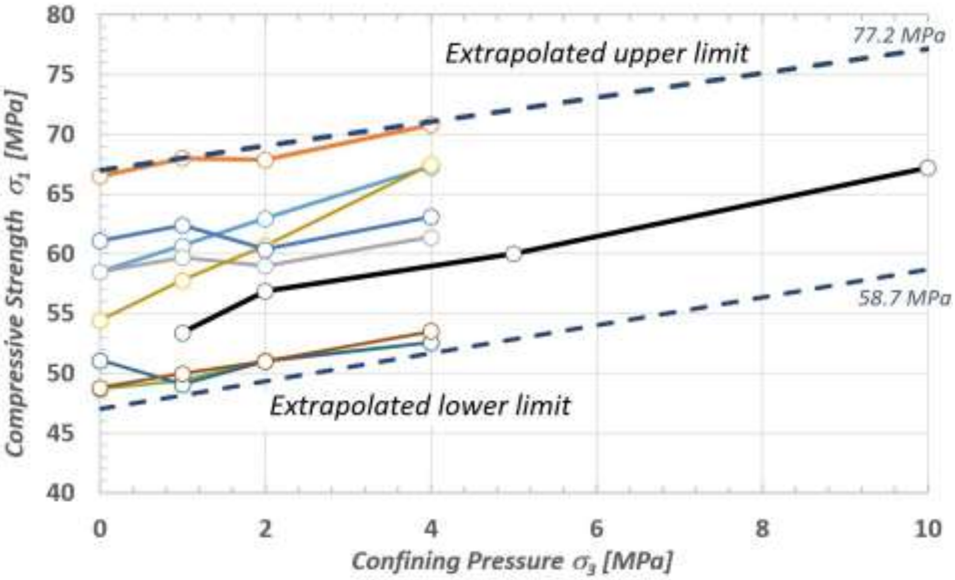

Fig. 8. Minimum, mean and maximum values of uniaxial and triaxial compressive strengths (σ_1) as a function of the confining pressure (σ_3) during the pressure load. The colors are representing different test specimens.

Despite the reduction in radial stresses, solution acts on the end faces of a barrier and leads to axial stresses. This stress is not critical for the core barrier due to the high strength and stiffness of Sorel concrete A1. However, as a result of the uniform loading of the end faces (plane strain conditions) significant shear stresses act on the contact zone with the rock. In order to be able to evaluate the resistance of the barriers to these stresses, the tensile and shear strengths of the contact zone including the EDZ were determined. The shear strength improves with increasing pressure on the contact surface. Consequently, a series of measurements were undertaken at different principal stresses. Information on shear strength with rock salt and the potash salt rock carnallitite are shown in Fig. 9.

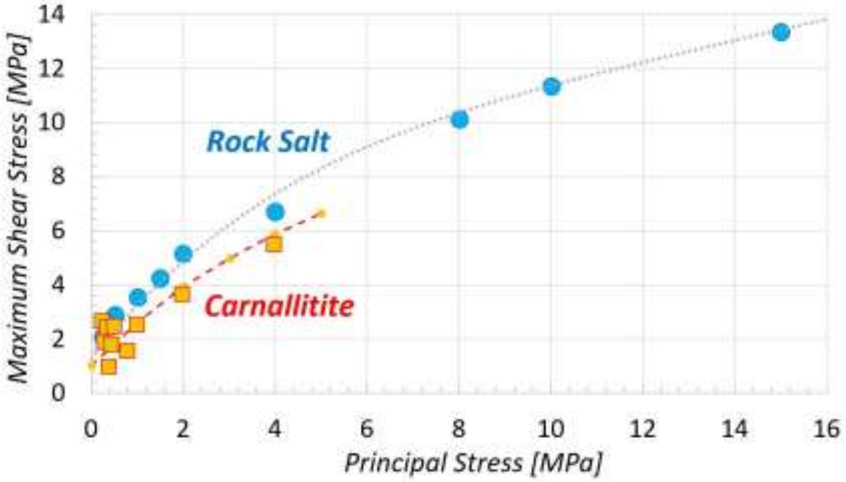

Fig. 9. Maximum shear stress (shear strength) of the contact of Sorel concrete A1 with rock salt and carnallitite as a function of principal stress (normal stress).

Uniaxial tensile strengths are lower compared to shear strengths. They almost reached values that can be predicted for the shear strength without normal stress. These values are 1.0 MPa for the contact with carnallitite and 1.3 MPa for test specimens with rock salt and Sorel concrete. In particular in the case of low strength values, the cracks occurred in the rock, i.e. in the EDZ. These findings clearly prove that the requirement of a good and firm bond between the Sorel concrete and the rocks is fulfilled. All design calculations show that failure of the structures is not possible. In the case of the principal stresses that occur, and taken into account the ratio of the front to the lateral surface of the barriers, the permissible shear stresses are far above the stresses that the solution can generate.

A solution pressure comparable to the radial stresses on the contact zone could, however, lead to an opening of cracks and could increase the permeability of the barriers. For this reason, a proof must be carried out, which in principle includes a comparison of the stresses caused by rock convergence and the build-up of a solution column. Particularly sensitive is the EDZ that is characterized by more or less cross-linked cracks and fissures. Likewise in this case, the pilot structures provided important information (cf. Fig. 10). They showed that after just a few years the radial stresses did not correspond to the original rock pressure, but are significantly higher than the fluid pressure expected at the respective depth. For example, stresses between 13 and 14 MPa are currently being determined at so-called pilot flow barrier A1 on the 950 m level. This important fact is a result of the low compaction behavior of Sorel concrete A1 and high rock convergence partially caused by the lack of anhydrite in the surrounding rock formation and the dominance of rock salt capable of creep, and potash salts. In analogy, the design calculations showed for other locations that the contact area remains overpressured and the level of restraint is always sufficiently high.

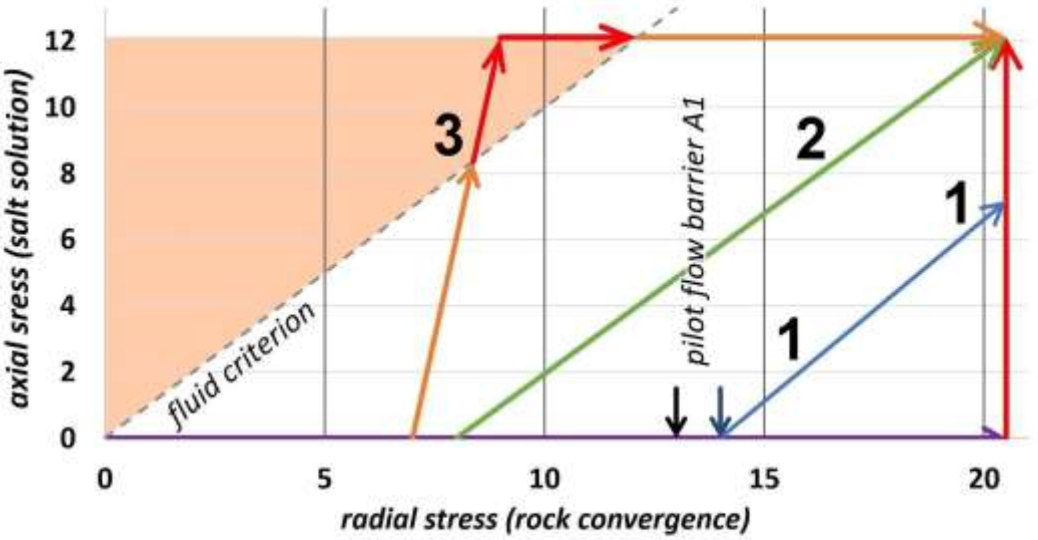

Fig. 10. Diagram illustrating the proof of tightness of the EDZ. In the case of path 1 (blue) and 2 (green) radial stresses that affect the EDZ and the barrier contour are larger than the stresses caused by the built-up of a solution column. In path 3, however, the radial stresses are exceeded (red arrows) so that the so-called fluid criterion is violated and cracks could open.

Seismic activities are additional loads, and according to the construction technology extraordinary load and design situations. They impact underground mining operations in a variety of ways, so that appropriate assessments and safety proofs are routinely carried out by BGE TECHNOLOGY GmbH. Without going into detail, some facts need to be emphasized that are beneficial for the stability of the barriers. First of all, underground in comparison to surface structures are less vulnerable, because they move with the rock, while structures above ground sway back and forth due to the effect of inertia.

As seismic activities are external dynamic load situations, the proof of resistance of the barriers is based on solid material properties, which are obtained under dynamic test conditions. Relevant are in particular the elastic material properties such as Young's modulus and Poisson's ratio, because they influence the shear and compression modulus and are parameters for evaluating the bending and shear rigidity. Fortunately, strength and Young's modulus increase significantly with the strain rate, a dependency that is often quantified with a dynamic increase factor (DIF). Another great advantage is the simple design of the barriers, the symmetry and dimensions that ensure sufficient torsional and flexural rigidity. A design earthquake is selected as the load which covers the predictable earthquakes (cf. DIN EN 1998-1/NA). All conducted numerical calculations show that cracking can be excluded.

QUALITY ASSURANCE MEASURES

To guarantee an optimal workflow and a barrier construction according to the requirements based on the experience of the construction sector a detailed quality assurance program was developed. It is described in a site-specific quality control and test plan that includes detailed information on the allocation of responsibilities, the sequence and type of actions necessary to meet the objectives, the testing parameters, acceptance criteria, and deliverables.

After the removal of foreign materials such as technical equipment an extensive site-specific survey starts. It includes, for example, mine surveying of the sites, geological mapping, and the performance of geotechnical measurements. Now the barrier construction can be planned in detail. In particular, the extent of the re-cutting work and the dimension of the barrier are determined. Fig. 11 shows a visual inspection of a barrier site during this working phase. Then, drilling of the backfill and vent boreholes and the shaping of the profile can be performed.

Open boreholes can still exist from the era of mining. They are catagorized according to their possible influence on the sealing effect of the core barrier. A range of magnesia binders has been developed for sealing these boreholes. The selection of the backfill material is based on the identified category of the borehole as well as its length and diameter. In most cases, a Sorel mortar is used that has a composition comparable to that of Sorel concrete A1. It is essential to compare the calculated borehole volumes with the building material volumes that is pumped in the borehole and hardens under pressure. These activities are followed by the cleaning of the site, the re-measurement of cavity shape and the final geological mapping. Now, a final check can be carried out to prove that the sections for the abutments and the core barrier can be filled without air voids. The aim is to achieve the shortest possible time from re-cutting the rock surface to concreting the Sorel concrete A1. Experience shows that a period of three months must not be exceeded in order to limit the extent of the EDZ to the required extent.

Fig. 11. Visual inspection of the location of a horizontal flow barrier in rock salt. On the right-hand side of the drift an air duct is installed to ensure ventilation.

The construction of the formwork walls for the concreting of the abutments is always based on a proof of stability considering static calculations (Fig. 12). The work ends with a control of final acceptance. The magnesium oxide and the aggregate are pneumatically conveyed to underground mix-pump-units. To guarantee undisturbed production and backfilling processes, tests of the technical equipment and the Sorel concrete are necessary. Quality specifications have been agreed with the suppliers of the raw materials. Moreover, quality checks of the raw materials, the fresh concrete mixtures and hardened test specimens ensure the conformity with the requirements [13]. For this purpose, two laboratories were installed at the Asse II mine. An above-ground laboratory is primarily intended for acceptance tests, and an underground laboratory for rheological tests. In the underground laboratory, measurements of the temperature (Fig. 13), the volume increase during hardening, changes in density, and the swelling pressure development of the Sorel concrete A1 are investigated (Fig. 14).

Fig. 12. Construction of a formwork wall shortly before completion for concreting an abutment.

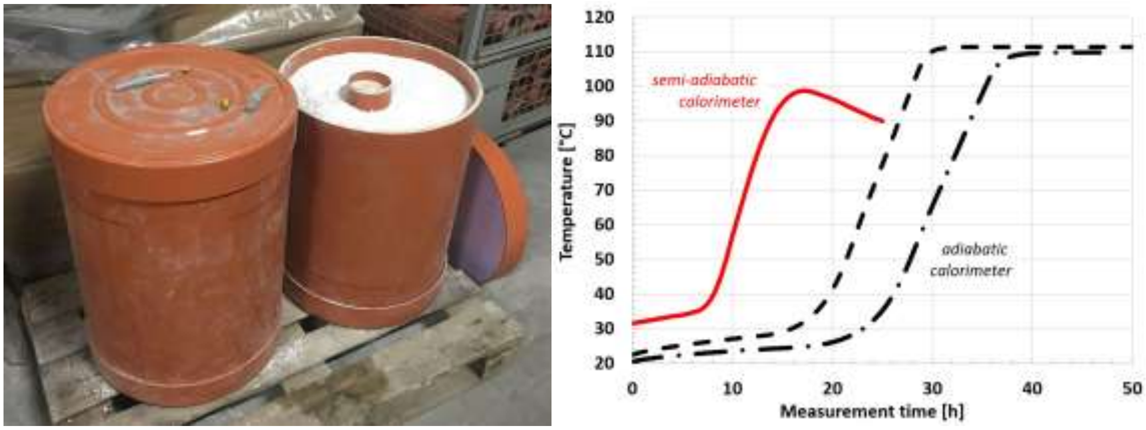

Fig. 13: Semi-adiabatic calorimeters for measuring the temperature development and preparation of test specimens (left). The gap between the pipe with Sorel concrete and the housing is filled with insulation material. The right diagram shows measured values of the semi-adiabatic calorimeter and an adiabatic calorimeter without heat dissipation to the environment (cf. Fig. 7, left diagram).

Fig. 14: Device for measuring the development of swelling pressure and temperature during hardening of Sorel concrete A1.

All test methods meet the requirements of maximum accuracy and sensitivity, in the sense that measured values change significantly when the properties of the concrete change. In addition, the test procedures were optimized according to the characteristics of the concrete. In this regard, BGE TECHNOLOGY GmbH used the comprehensive experience gained from various backfilling and sealing measures. The final proof of complete filling is based on measurements of the filling height. Furthermore, it is possible to compare the volumes of the concrete with the cavity volumes.

Solid material properties are determined by qualified external test institutes according to comprehensive test instructions. Most of these methods are based on state-of-the-art technology of material and rock science. In order to quantify the compaction behavior of Sorel concrete an innovative test procedure was developed [14]. It is based on creep tests that take into account the convergence rates of the location.

With regard to the evaluation of the findings and the implementation of conformity assessments, it is of great advantage that Sorel concrete A1 and variations of this recipe are also used as backfilling material. As a result, there is a unique data set for the individual material properties. Consequently, it is possible to precisely determine statistical parameters and influencing factors. The standardized concept of concrete families (e.g. [15]) makes it possible to link data sets on the properties of these recipe variations. In this way, the quality of the data evaluation can be further improved, and it can be reliably demonstrated that the structures meet the requirements in the short and long term.

CONCLUSIONS

Since 2007 barriers have been built at the Asse II mine that should control the flow of solutions and protect the chambers containing radioactive waste. They have a simple design, which allows a quick construction and simplifies the work planning at the site, taking extensive backfilling measures into account. The barriers consist of a special inorganic concrete using magnesium oxide as binding agent, which was developed on the basis of a detailed catalog of criteria. The verification of the function of the barriers is based on the proven and tested concept, comparing actions and resistances, as well as considering uncertainties and safety factors. A set of safety proofs is performed separately for the hydraulically relevant areas of the barriers. First, it is checked whether the barrier meets the tightness requirements after the hardening of the concrete. Then, it is checked whether chemical or mechanical interactions that could occur in the future could lead to the formation of cracks or whether an increase in permeability is possible due to the solution pressure. The safety proofs can be provided through calculation or design assisted by testing (e.g. pilot barriers). A quality assurance program enables an undisturbed work flow and ensures the validity of the assumptions made in the safety proofs.

The development of this concept is based on the experience and knowledge of BGE TECHNOLOGY GmbH, which was gained during the implementation of national and international radioactive waste disposal projects. As a conclusion, special care was taken to develop a universally applicable modular concept. Alternative sealing materials or host rocks are integrated by choosing other or additional input parameters. Depending on the actions to be taken into account, safety proofs can be neglected or added as additional modules. In order to perform appropriate modifications and for checks of completeness, compilations of features, events, and processes (FEP) can be used.

Up to now, the concept has been successfully adapted to a project of borehole sealing. In this case, taking into account the possibility of the disposal of heat-generating waste, it was necessary to add a module to prove the thermal stability of the sealing material. Recently, the concept was also modified according to the conditions of the Morsleben repository for radioactive waste. In the context of the closure of this LILW repository seals must be erected situated in the access drifts to the disposal areas. In this case, lower convergence rates of the rocks required the development of a sealing material that has an even lower compacting capacity than Sorel concrete A1. This work has been successfully completed in the meantime.

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