INVESTIGATION OF A SALT-CONCRETE SEAL IN THE ASSE SALT MINE

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ABSTRACT

In context with the closure of the Morsleben repository (ERAM) the potential migration of brine and gas passing salt-concrete seals has to be evaluated. According to present knowledge the contact zone between the sealing body and the surrounding rock is an important migration path and thus is decisive for the permeability of the seal. In order to show that the hydraulic conductivity of the seal is sufficiently small, the permeability of the contact zone has to be quantified. Respectively, it has to be shown that no defects exist in the contact zone leading to an intolerable degree of permeability of the seal, i.e. exceeding a permeability of 10^{-18} m^2 on average. According to technical regulations in Germany investigations on comparable structures are required to assess the tightness of contact zones.

For this purpose a 10-year-old salt-concrete seal in the Asse mine in Lower Saxony has been investigated, whose structure is comparable to the seals planned for the ERAM. This seal had been built within the framework of an abandoned research project. A detailed investigation concept comprising in-situ measurements and laboratory tests was developed and a method has been established to transfer the boundary conditions of the Asse mine to the ERAM, where the seals will be constructed.

In-situ measurement results from the Asse seal show permeabilities in the range between $10^{-20}\ m^2 < k < 10^{-24}\ m^2$ at the contact zones to the walls and the floor, which indicates that the required permeability of $k \le 10^{-18}\ m^2$ is achieved. At the roof, however, higher permeabilities in the range between $10^{-12}\ m^2$ to $10^{-19}\ m^2$ were measured indicating a strong heterogeneity of the contact zone to the roof. The results of ultrasonic measurements underlined the heterogeneity of the roof area, which shows defects and faults, whereas no heterogeneities were detected at the walls and only very few, isolated ones in the floor. Altogether, the results show that the required tightness will be achieved by constructing comparable seals in the ERAM, although the quality of the contact zone to the roof has to be improved.

INTRODUCTION

In the former German Democratic Republic (East Germany) the abandoned salt mine of Bartensleben was selected to serve as a repository for low and intermediate level (LLW, ILW) radioactive waste. Located near the village of Morsleben in the Federal State of Saxony-Anhalt, this mine was named “Repository for Radioactive Waste Morsleben (ERAM)”. The decision to establish the repository was based on safety and technical-economic studies performed in the 1960s. It was designed, constructed and commissioned from 1972 to 1978. Following several studies and the successful demonstration of the disposal technologies used, a first operational licence was granted in 1981.

After German reunification (October 3, 1990) the Federal Government of Germany took over the responsibility for the repository. The Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) acts on behalf of the Federal Minister for the Environment, Nature Conservation and Nuclear Safety (BMU), who represents the German Federal Government. The DBE then became operator of the repository on behalf of the BfS. The final disposal of waste was stopped in 1998. The BfS concluded contracts concerning backfilling and closure of the Morsleben repository, which is presently being planned [1,2].

In the context of the closure of the ERAM, 21 drift seals must be erected. Situated in the access drifts to the disposal areas these drift seals are essential to long-term repository safety. To guarantee compatibility of all closure measures planned [3], salt-concrete is the preferred construction material for the seals.

The hydraulic resistance of drift seals depends on three main elements: the excavation damaged zone (EDZ) of the drift, the sealing body, and the contact zone between sealing body and the surrounding salt. Their adequate hydraulic resistance has to be proved [2,4,5], i.e. the potential migration of brine and gas passing the salt-concrete seals has to be evaluated. According to present knowledge the contact zone between the sealing body and the surrounding rock is an important migration path and thus is decisive for the permeability of the seal.

In order to show that the hydraulic conductivity of the seal is sufficiently small, the permeability of the contact zone has to be quantified. Respectively, it has to be shown that no defects and faults exist in the contact zone leading to an intolerable degree of permeability of the seal, i.e. exceeding 10^{-18} m^2 on average. According to technical regulations in Germany [6, 7] investigations on comparable structures are required to assess the tightness of the contact zone.

For this purpose:

- a 10-year-old salt-concrete seal in the Asse mine in Lower Saxony is investigated, whose structure is comparable to the seals planned for the ERAM. This salt-concrete seal was built within the framework of a research project.
- a detailed measuring concept has been developed [8] and
- a method to transfer the boundary conditions of the Asse mine to the ERAM, where the seals will be constructed, has been established.

Construction Process of the Salt-Concrete Asse Seal

The following paragraphs give a short description of the construction process to permit an appropriate interpretation of the measuring results.

The dimensions of the Asse seal are 8.0 m in length, about 5.5 m in width, and up to 3.4 m in height, covering a total volume of 128 m^3. The Asse seal is made of salt-concrete, 1 m^3 of salt-concrete consists of 380 kg of cement, 169 l = 198 kg of NaCl-saturated brine and 1496 kg of crushed salt. The seal was erected in two phases. 4 concreting sections were built during the first phase and 3 sections were built during the second phase. A gap of about 10 cm was left in the roof and was later on filled with salt-concrete by hand, i.e. the gap was stuffed. Finally, the contact zone of the former gap area and the rock salt was injected with cementitious grout (Fig. 1).

Fig. 1. Construction phase of the salt-concrete Asse seal showing salt-concrete segments, the partly filled gap and the injection pipes (left) and start of the investigation program (right).

Steps to Prove the Tightness of the Seal

The tightness of the seal is proved in three main steps: determination of the permeability at representative measuring positions, determination of defects and assignment of the local results to the whole contact zone by statistically representative investigation methods, and application of the investigation results to the evaluation of the planned ERAM seals. When transfering the results to the ERAM seals it must be taken into account that the stiffening effect of the anhydrite layers and the lower depth of the ERAM lead to a slower evolution of creep induced rock pressure onto the seals.

The following list shows in detail the investigations and/or measurements that have been performed [8]

(1) Determination of the permeability at representative measurement positions:
- in-situ permeability measurements with dry air in the sealing body, the contact zone and the EDZ. Measurements were performed in 13 boreholes in the roof, wall and floor. Some of these tests were designed as interference tests in axial direction
- laboratory permeability tests to verify the in-situ measurement results
- determination of water content to prove the assumption of an air-filled pore volume or to correct the measurement results, respectively
- in-situ permeability measurements with brine for saturation control

(2) Statistically representative investigations:
- borehole endoscopy for:

  - visual evaluation and structure survey of the investigated seal and surrounding rock
  - macroscopic detection of cracks and defects in the borehole
  - final determination of measurement positions
- Ultrasonic measurements to assign the local borehole measuring results to a statisticallyrepresentative part of the contact zone with the aim of determining an "effective hydraulic seal length" in the end. For this purpose the entire contact zone is examined by ultrasonic measurements in approx. 30 boreholes. Thus, the state of the contact zone in its whole is registered by determining location, number and dimensions of defects.
- Core samples from 8 boreholes which contain exactly the contact zone will be used for detailed defect analysis by core-scanning and tomography methods

(3) Application to ERAM conditions:

- determination of the initial stress state and the stress and deformation history by analysis of measurement results available from the Asse mine [9, 10, 11]
- stress measurements by hydraulic fracturing to investigate the weakness of the contact zone by determining the least principal stress and its direction
- material investigations using core samples from roof, walls and floor of the Asse seal to evaluate mechanical parameters (e.g. compression/tensile strength, Young's modulus, Poisson ratio) and hydraulic parameters (e.g. threshold pressure, permeability, porosity, recrystallization)

Presently, all in-situ investigations are completed. The results are described in the next chapters.

Results of In-Situ Measurements

Permeability Measurements

Pulse-tests were employed for most of the permeability measurements with gas being used at pressures of 0.6 and 1.2 MPa and an observation phase of two to four days. Additionally, constant-pressure-tests were performed in the roof. Relevant results of the tests establishing the permeability to gas are given in Fig. 2. Fig. 2 shows that in the contact zone to the walls and the floor the permeability is low, i. e. $k < 10^{-22}$ m². In the unfavorably constructed roof a wide range of permeabilities between $2.1 \cdot 10^{-13}$ m^2 and $6.5 \cdot 10^{-19}$ m² was determined. Consequently, the interference tests did not show any pressure response in the boreholes nearby at the wall and the floor. Evidently no zone of higher permeability exists in this area of the seal. In the roof, however, pressure responses were measured.

In addition to that, permeability tests in which brine was used as test medium were performed at the southern and the northern wall. They showed permeability in the range of 10^{-19} m^2 to 10^{-21} m^2. Thus, brine tests established permeabilities that were up to two orders of magnitude higher than those found in the gas tests performed at the same position. This effect is related to secondary leaching and precipitation processes within the borehole contour at the measuring positions.

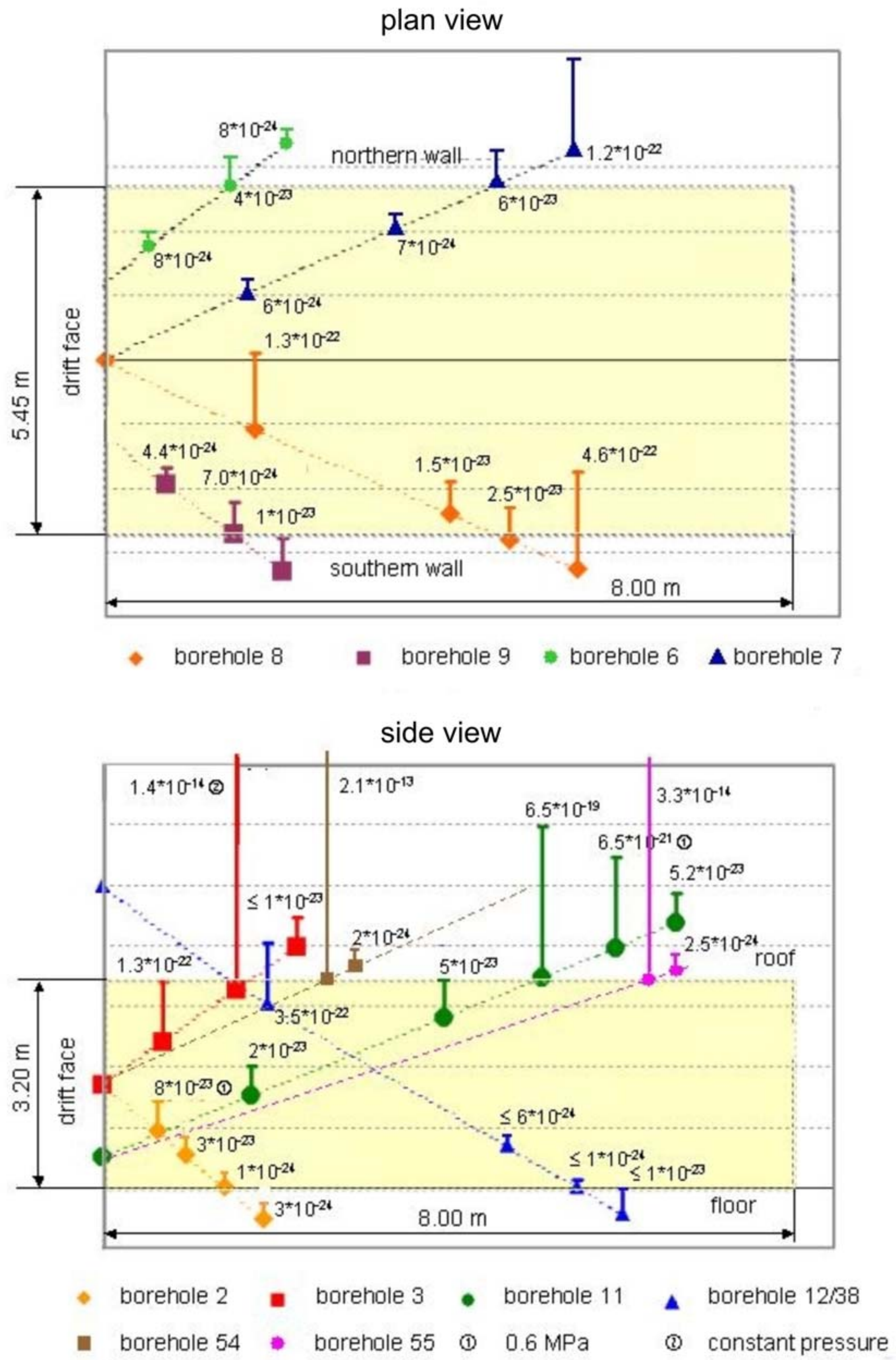

Fig. 2. Permeability to gas [m²] mainly resulting from pulse-tests performed at 1.2 MPa.

Finally, the measuring results for the salt-concrete sealing body, the former EDZ and the contact zone can be summarized [12].

The salt-concrete body showed a permeability to gas in the range between $6.0 \cdot 10^{-19}$ m^2 to $4.4 \cdot 10^{-24}$ m^2 and a permeability to brine of $4.1 \cdot 10^{-20}$ m^2 to $9.0 \cdot 10^{-21}$ m^2. The gas permeability measured at the same positions, however, showed values between $6 \cdot 10^{-19}$ m^2 and $7 \cdot 10^{-23}$ m^2.

In the rock salt contour (former EDZ) close to the former drift a permeability to gas in the range between $6.5 \cdot 10^{-21}$ m^2 to $2.0 \cdot 10^{-24}$ m^2 was measured. The highest permeability of $6.5 \cdot 10^{-21}$ m^2 arose in the former EDZ of the roof. This low permeability of the former EDZ is interpreted as a result of creep and stress redistribution that has already taken place.

The contact zone to the walls and the floor showed a permeability to gas in the range between $6 \cdot 10^{-23}$ m^2 and $1.0 \cdot 10^{-24}$ m^2 and a permeability to brine in the range between $8.0 \cdot 10^{-21}$ m^2 to $1.4 \cdot 10^{-21}$ m^2. These results indicate a good adhesion of the salt-concrete body to the rock salt contour. In the contact zone to the roof a permeability to gas in the range between $2.1 \cdot 10^{-13}$ m^2 to $6.5 \cdot 10^{-19}$ m^2 was measured. The high permeability in this area arises from the insufficient quality of the salt-concrete which fills the 10 cm gap at the roof (Fig. 1). This conclusion is drawn from measurements that were performed in the former EDZ with a minimum distance of about 1.5 cm to the contact zone (borehole no. 54, 55) by fixing a packer in the former gap area with its inner border in line with the contact zone. These measurements proved that the high permeability was not caused by the contact zone itself but by defects and large pores of the salt-concrete in the gap area.

Stress Measurements

Ten years after having constructed the seal the hydraulic fracturing stress measurements in the contact zone showed well-closed shape linkage. In the first measuring campaign the largest stresses were determined in the contact zone to the floor and the southern wall in the middle of the seal showing values up to 15.6 MPa. Lower values of 3.5 to 6.6 MPa were measured at a distance of 1.5 m from the drift face. However, the smallest principal stress was measured in the contact zone to the roof of the middle section of the seal showing 2.1 MPa, while in the surrounding rock salt, the measured compressive stresses are again very high, i. e. about 15.7 MPa. After having widened the drift in front of the seal in a second measuring campaign stress values of 2.5 MPa to 6.9 MPa were determined in the northern wall of the seal. The results [13] are given in detail in Table I.

At the floor and the walls the results of the hydraulic fracturing tests showed intact adhesion of the salt-concrete body and the rock salt contour. In the floor the least value of tensile fracture failure strength indicates lower tensile strength in this area in general. However, least principle stresses of 2.1 MPa in the roof, 2.5 MPa at the wall and 3.5 MPa in the floor had no negative influence on the local tightness of the seal as the permeability was determined to $k = 6.5 \cdot 10^{-19}$ m^2, $4 \cdot 10^{-23}$ m^2, and $1 \cdot 10^{-24}$ m^2 at identical positions. In the roof, however, primary tightness was not achieved because of defects and pores in the gap area. This result underlines again the low quality of salt-concrete in the gap, which evidently has not improved by the injection made.

The orientation of the cracks induced by hydraulic fracturing show that the contact zone and the rock salt of the former EDZ are the weakest elements. All of the cracks have been detected within these elements. In no case was the salt-concrete body affected by hydraulic fracturing induced cracks.

Table I. Shut-in Pressures and Tensile Fracture Failure Strength

Quantity	Position	Measuring results
Shut-in pressures [MPa] after1 hour	Floor (front/centre)	3.5/15.6
	Northern wall (front/centre)	2.5/6.9
	Southern wall (front/centre)	6.6/13.1
	Roof (front/centre)	No pressure built up/2.1
Tensile fracture failure strength [MPa]	Floor (front/centre)	2.6/0.9
	Northern wall (front/centre)	4.4/5.3
	Southern wall (front/centre)	5.2/9.6
	Roof (front/centre)	-/3.6

Defect Determination

For ultrasonic measurements the reflection method [14] was mainly employed, using 26 boreholes. The reflection measurements covered the whole salt-concrete seal contour. The measuring equipment consisted of 1 emission unit and 4 receiving units, which were positioned at equal distances of 140 mm. The length of each measurement profile was 8 m with a distance of measuring positions of 200 mm. At each measuring position 7 signals were emitted on frequencies of 28 kHz, 40 kHz, 56 kHz, 80 kHz, 112 kHz, 160 kHz and 224 kHz. The results are given in Fig. 3. Corresponding to the results of the permeability and hydraulic fracturing measurements, significant reflections were received from the roof. The zone of extensive reflections is estimated to be about 10 cm wide. At the walls, however, no reflections occur at the contact zone showing a very good adhesion of the salt-concrete and rock salt contour as well as comparable properties (density and p-wave velocity) of salt concrete and rock salt. Single reflections from the floor showed small, locally spread and weakly marked heterogeneities. The evolution of the results for the entire contact zone is given in Fig. 3. The fact that a measuring frequency of 224 kHz could be used underlines again the integrity of the structure except for the roof. Otherwise, the high frequent signals would have been back-scattered without showing any result at all.

For the determination of the effective hydraulic length, additional GPR measurements were performed at the drift face of the seal to find out whether a disturbed zone exists close to the drift face originating from unfavorable stress concentrations and the plane stress state at the drift face end of the seal. So far the GPR measurements recorded a disturbed zone inside the seal with a maximum distance of 1.60 m from the drift face.

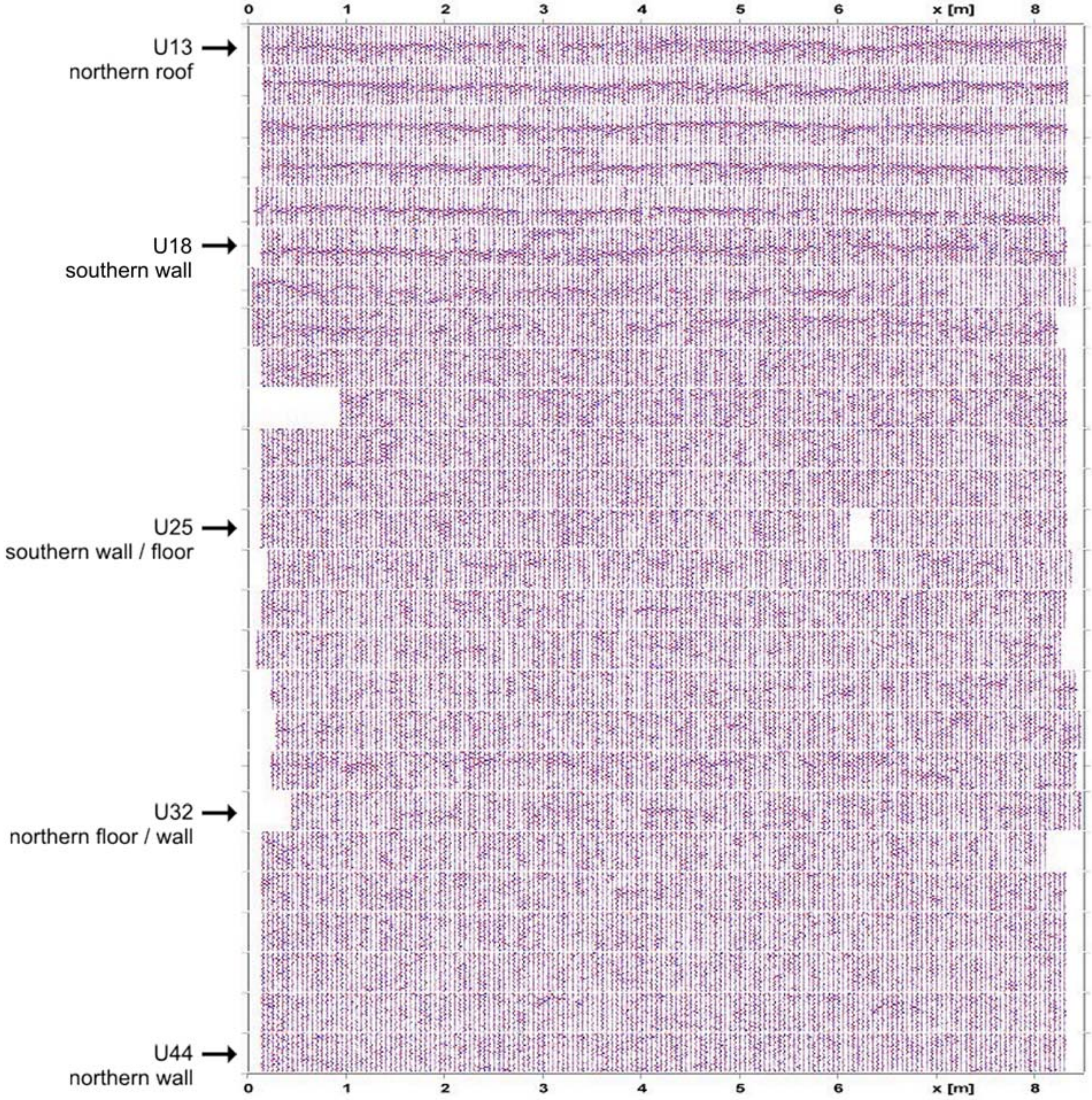

Fig. 3. Evolution of the reflection measurement results of the salt-concrete seal focussing the contact zone [14].

Laboratory Tests - Inspection of Core Samples

In the context of the laboratory tests 8 boreholes were drilled parallel to the contact zone to gain core samples containing the contact zone. In Fig. 4 two core samples are shown as an example. One core sample includes the contact zone to the wall, the other one the contact zone to the roof. The contact zone to the wall shows a very good adhesion of the rock salt and the salt-concrete body. The contact zone to the roof is of significantly worse quality. These results again comply with the results of the permeability tests, the hydraulic fracturing tests as well as the ultrasonic measurements.

Fig. 4. Core sample no. 52 from the roof (left) and core sample no. 48 from the wall (right).

The preparation of the actual laboratory tests has just started, results are not yet available.

Application of Results to ERAM Conditions

In order to transfer the site specific conditions at the seal position in the Asse salt mine to the site specific conditions of the ERAM seal positions, the state of the Asse seal position and its history is modeled numerically taking into account measuring results. By modeling a comparable seal at the ERAM seal positions the point of time is assessed when comparable tightness can be expected at these positions in the ERAM. This work is in progress.

First Rating of the Results Available

Except for the roof, the permeability of $k < 1 \cdot 10^{-22}\ m^2$, which is indeed very small, in the contact zone indicates a good adhesion of the seal to the surrounding rock. This result is underlined by the compression stress measured at most of the positions of the contact zone. Even at those positions showing smaller principal stresses in the floor and roof the permeability is determined to $k < 6.5 \cdot 10^{-19}$ m². The results of the hydraulic fracturing investigations clearly indicate that the higher permeability measured in the roof is not a result of missing rock pressure but of bad quality of the hand filled gap, which has not significantly improved by grouting. The results of the permeability tests are confirmed by the results of the ultrasonic measurements showing mainly that the former gap area is a weak zone with defects and large pores, which is underlined again by visual inspection of core samples. The permeability in the contact zone of the roof is bounded by $k = 6.5 \cdot 10^{-19}$ m^2, which is the minimum permeability measured. Thus, good quality can be attained in the roof, too. Nevertheless, the lesson had to be learnt that the construction must be modified to guarantee an excellent quality of the contact zone to the roof.

CONCLUSION

The results from investigating the 10-year-old salt-concrete seal in the Asse salt mine prove that tightness can be achieved in the contact zone of a salt-concrete drift seal inside a rock salt environment. Nevertheless, the lesson had to be learnt that the quality of the contact zone to the roof has to be improved mainly during the construction phase since subsequent grouting does not automatically lead to a good result.

Finally, it can be concluded that a permeability of $k \leq 10^{-18}$ m^2 on average can be reached by constructing a salt-concrete seal in-situ, which complies with the permeability requirements for the ERAM seals.

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