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Fluidic functional verification for closure structures and Fluid-based Sealing of the Contact Zone – 23450

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SUMMARY

The construction of fluidically sealing drift seals is an important prerequisite in salt mining for safeguarding production, minimizing impacts on the environment and using the existing mine openings for the emplacement of environmentally hazardous substances/radioactive materials. In this context, the proof of the sealing function of the drift seals is an essential prerequisite for the operation and/or use of the underground cavities. In this paper, a concept is presented that provides proof of the sealing function without damaging the contact area.

INTRODUCTION

The conventional concepts for functional verification of erected drift seals are based on:

1. In situ permeability studies for:
    - Characterization of the rock mass in the installation area of the sealing segment for the site selection and determination of the required preparation of the contour of the opening (e.g. recutting of the surface).
    - Determination of the permeability of the remaining rock mass as a basis for the material selection and dimensioning as well as the model-based prediction of flow processes through the structure (functional verification).
2. Laboratory determination of the fluidic properties of the used construction and sealing materials.
3. Local testing of the installed structure via exploratory drilling or fluidic testing using pressure chambers.

The examinations mentioned under points 1 and 2 are always required for the functional verification of the drift seal. The assessment of functionality via individual exploratory boreholes intersecting the structure (point 3) yields selective statements on the fluidic situation at the points where the boreholes penetrate the structure or along the boreholes in the structure. To minimize the number of boreholes in a sealing structure, the scope of investigation is limited to a few local points in the structure. The point-by-point investigation via boreholes can only be considered of limited value for assessing the integral effect of drift seals.

In the past, integral testing of structures using pre-installed pressure chambers in drift stumps was always linked to research projects. The restriction of this test concept to roadway stumps and the great effort involved in mining technology ruled out the application of this concept for the fluidic functional verification of safety-relevant drift seals in the underground. In addition, materials and methods for any required tempering and sealing were selected, parameterized and tested in situ.

The starting point for the development of the verification concept is the specific fluidic situation for sealing segments made of cohesive material (cements, mortars, concretes) in contact with salt rock. A special situation for sealing exists in the contact zone between the construction material and the formation. With the exception of MgO-based construction materials, an active sealing by volume increase, as is specifically used in the application of bentonite as sealing material, cannot be assumed for cement-based sealing materials. In many cases, contact with the formation results in the formation of an area with increased permeability, as shown schematically in Figure 1.

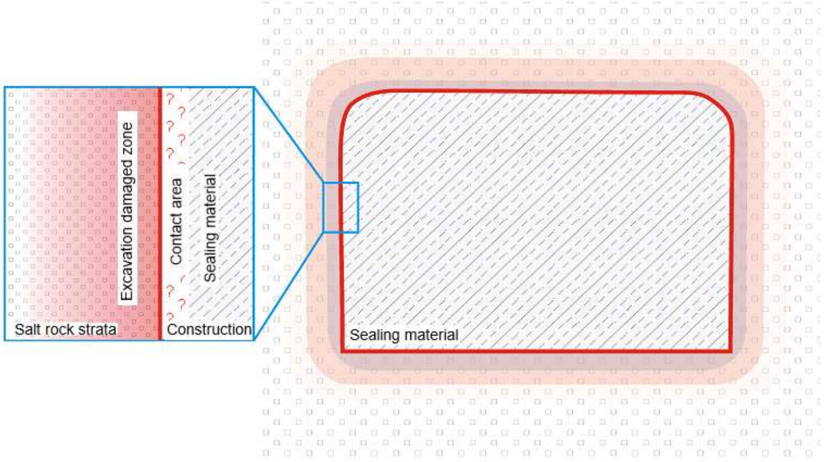

Figure 1 – Schematic display of a vertical cut through a sealing segment with details of the contact between the construction material and the formation. [1]

The causes for the increased permeability are multiple and overlapping. These include:

a. Thermal expansion and contraction of rock and construction material in the course of the temperature regime of the construction of the structure.
b. Shrinkage of the construction material in the course of the setting reaction.
c. Interaction of structure and rock contour (constraint stresses).

This can lead, spatially limited to the contact area between construction material and rock, to higher permeable pathways locally and over the length of the structure, which determine the integral permeability of the entire structure. In addition, these pathways determine the mass transport and the time required for dissolved components to pass through the structure.

Within the research project "Fluidic functional verification for closure structures and liquid-supported sealing of the contact area" (FKZ: 02 E11748A, funded by the Federal Ministry for Economic Affairs and Energy) a concept for the integral testing of constructed drift seal has been developed. Furthermore the objective assessment and, if necessary, the verification of the fluidic sealing effect were part of this research project. The concept has successfully been installed and tested in a dam structure in the Teutschenthal mine. With this test concept, the necessity and requirement for an objective proof of the fluidic functional safety depending on the load scenarios and the application conditions of the drift seal, which is justified under licensing law, is met. [2]

In the following sections of the paper, a number of results and findings are discussed. These include the following topics:

1. Flow processes and influences during in situ testing
2. Test setup
3. Tests on the drift seal
4. Construction material quality
5. Summary and outlook

FLOW PROCESSES AND INFLUENCES DURING IN SITU TESTING

According to Weber [1], the following processes and influencing variables are relevant for the flow process, independent of the flowing fluid, in a structure or drift seal:

- The geometry of the flow cross section and knowledge of the extent of areas present in a structure with different fluidic properties (e.g. loosening zone rock mass, contact area between sealing element and rock mass, and sealing element made of construction material).
- The fluidic properties of the areas in the structure mentioned in the previous point and, if applicable, their spatial and time-dependent changes.
- The initial pressure and temperature distribution in the structure and in the rock and its change over time.
- Pressure and temperature curve during testing.

In addition to these facts, according to Weber [1] there are different influences for the gas and liquid flow:

- Influence of the effective phase permeability (also effective permeability) of the individual areas due to the spatially and temporally variable liquid saturation in the pore space - two-phase flow (e.g. change due to saturation in liquid flow or drying in gas flow),
- Secondary reactions in individual areas of the structure in contact with the fluid, which may influence the permeability, porosity and pore space saturation (e.g. due to the setting reactions of the construction material, the swelling or shrinkage of the construction material and/or the rock).

The influences mentioned are effective on a laboratory scale and in large-scale structures. They vary over the length of the structure and the cross-section. Furthermore, they change over time as a function of the flow processes.

Despite or precisely because of these mutually overlapping influencing processes, large-scale fluidic in situ testing provides the proof of function of a sealing structure. A prerequisite for the evaluation and informative value of the in-situ structure tests is, as far as possible, to determine the above-mentioned properties and processes, which can be determined in the laboratory and at the site via in situ investigations, sufficiently accurately, if necessary with possible fluctuation ranges. This applies, for example, to the permeability and porosity distribution in the loosing zone (e.g. excavation damage zone) of the formation and in the intact rock mass, as well as to the permeability and porosity of the sealing material.

The use of the mentioned parameters, functions and information serves as preliminary information for the parameterization of the different flow areas in the numerical model for the evaluation of the in-situ tests and thus enables the identification of the permeability in the contact area between the sealing segment and the rock mass. Due to the low permeability of the sealing element and the generally low permeability level of the undisturbed, intact zone of the formation, the contact area between the sealing element and the rock mass is often of decisive fluidic importance for the overall system. A possible arrangement of the test system is described in the following chapter.

TEST SETUP

Considering the above-mentioned limitations for the fluidic characterization of a structure via boreholes and pressure chambers in drift stubs, a concept for the integral fluidic testing of constructed sealing segments was developed and successfully implemented on a large scale.

The basic concept of fluidic testing of a concreted sealing segment is based on the installation of at least three radially circumferential pressure chambers distributed along the length of the structure in the contact area between the construction material and the rock mass, as shown in the schematic display in Figure 2. These control chambers (CC) are installed as flexible hoses in close contact with the drift contour.

By inflating these hoses with compressed air, positive contact between the control chambers and the rock mass is established for the period of concreting. After the construction material has set, the pressure is relieved from the hose lines. The resulting cavities of the relieved hoses form the control chambers for fluid pressurization. Figure 3 shows the actually installed system. By this, the changing permeability of the contact zone, e.g. due to rock creep, can be observed over a longer period. If the contact between the construction material and the rock is improved and closed further by injection measures, the inflow of injection material into the control chambers can be prevented by re-inflating the hoses. After the injection, the control chambers remain available for pressure application and testing of the structure.

At least three pipelines are connected to each control chamber. A pressure pipeline ensures inflation and depressurization of the hoses (Figure 2). Two further pipelines enable pressurization and depressurization of the control chambers.

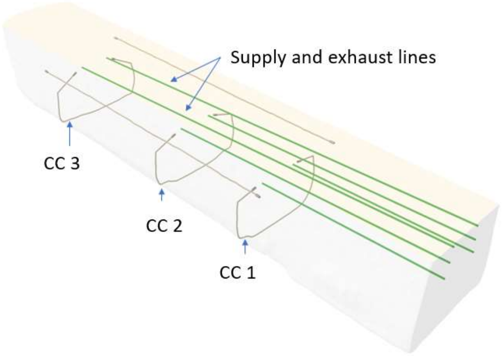

Figure 2 – Illustration of the control chambers - with supply and exhaust lines.

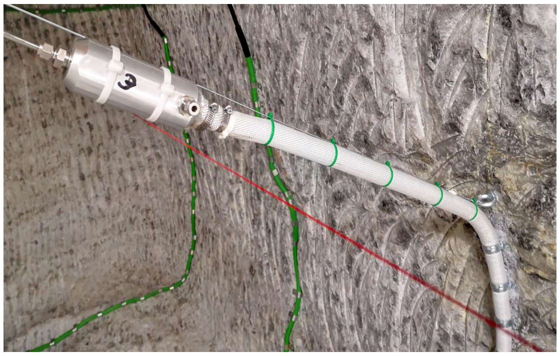

Figure 3 – Installed control chamber.

Via the control chambers, pressurization/fluidic testing of the contact between construction material and rock with gas and fluid is possible. These tests can be performed via a pressure pulse with a constant volume flow or a constant fluid pressure.

In the basic concept, fluid pressure is applied to the central control chamber and the pressure response in the surrounding control chambers is measured. Based on the geometry of the structure, the installed volumes of the chambers and pipes, and the flow lengths, a numerical model of the dam structure is created. Numerical parameter identification is used to recalculate the process measured in situ in the model and to identify the effective permeability in the sections of the structure between the control chambers via parameter variation. The model-based evaluation of the pressure reactions in the three control chambers enables the determination of the integral permeability of the structure in the contact between construction material and rock in the section of the structure between the tested control chambers.

After completion of the tests, it is possible to fill the control chambers with construction material, but this is not necessary due to their arrangement perpendicular to the direction of flow. The plastic pipes of the feed lines to the control chambers are recovered by drilling along the entire length of the feed line. After this, the pipes are backfilled to a suitable quality, e.g. with the sealing material of the structure, in order to seal the technically induced pathways. The test results on the half-dam are presented below.

TESTS CARRIED OUR ON THE DRIFT SEAL

As part of the STROEFUN project, the test concept shown here for the in-situ proof of function was implemented in a large-scale dam structure at the Teutschenthal mine in the third project phase. A drift, with a height of approximately 4.5 m, a length of approximately 15 m and a width ranging from 2.5 to 3.1 m was excavated in rock salt for the purpose of this project. In this opening, the high half-dam was constructed as shown in Figure 4. Prior to the construction, the installation of the required control chambers and injection pipes (Figure 5) required for the injection of the contact area between the construction material and the rock had been installed. In gas pressure tests over the installed three control chambers, the fluidic effect of the structure is assessed section by section.

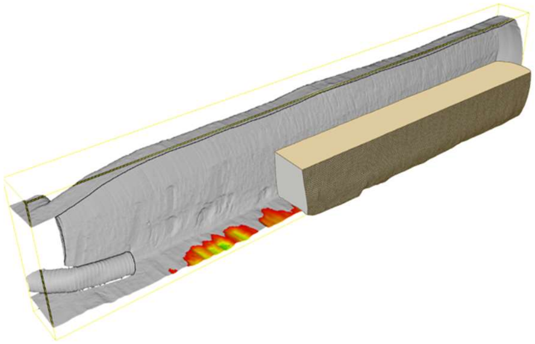

Figure 4 – Sectional view of site model with the dam structure.

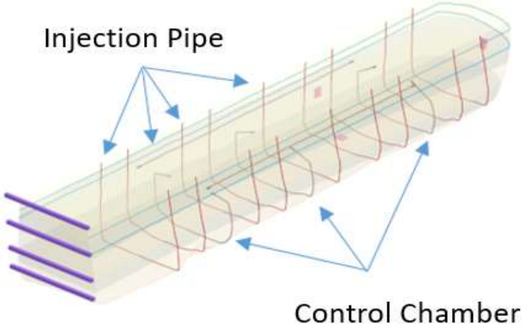

Figure 5 – Overview of the installed measurement, test and injection infrastructure.

Test results demonstrate increased permeability of the contact area between the sealant and the rock. In Figure 6. The pressure hydrographs for an impulse test are shown as an example.

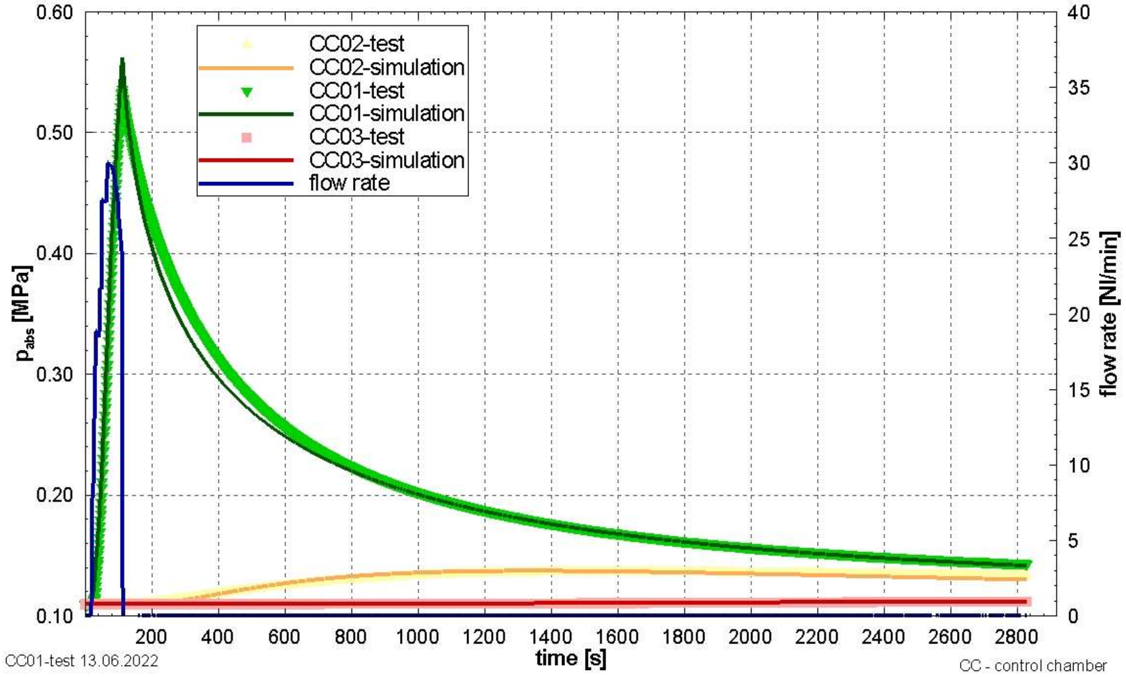

Figure 6 – Pressure and flow rate hydrographs of the pulse test on 06/13/2022 - measured values and model fit.

In the evaluation of the in-situ testing of the structure (Table 1), a reduction in permeability for the contact area between the construction material and the rock mass can be observed.

Table 1 – Evaluations of integral permeability between control chambers.

Date of measurement	Pressurized CC	Permeability between CC 1 and CC 2 [m²].	Permeability between CC 2 and 3 [m²].
21.01.2022	01	$8{,}0\text{-}10^{-15}$	$3{,}0\text{-}10^{-15}$
13.06.2022	01	$7{,}0\text{-}10^{-15}$	$9{,}0\text{-}10^{-16}$

The tests proved that there are higher permeable path properties in the contact area between the construction material and the rock. Over the integral control area of the chambers, these result in the permeabilities mentioned above. When assessing these results, it must be taken into account that the tested half-dam is not fully restrained in the rock contour.

CONSTRUCTION MATERIAL QUALITY

For the possible construction of a dam structure for the shielding of high-level radioactive waste in salt, a Sorel cement mixture is to be used in Germany [3]. At the start of the project, the so-called A1 formulation was used as the current state of the art, based on the following composition [4]:

- 11.3 % MgO
- 63.7 % Salt
- 25.0 % $MgCl_2$ solution

Due to the fact that the A1 formulation has already been applied to drift seals built in the Asse II Mine [4], it is possible to use existing experience, to compare results and thus to base further development on a solid technical foundation.

In order to gain initial experience when it comes to the handling of the construction material and to investigate the bond between batches mixed and placed with a time interruption, a two-layer concrete block was cast with two different batches of Sorel concrete. In this case, the two batches where mixed and placed 20 hours apart. Despite adherence to the composition, supernatant liquid appeared on the, now hardened, suspension introduced the day before at the beginning of the second day. This was documented and the second batch of suspension was placed on top of the first hardened material. After half a year, core samples were taken from the contact area for investigation. Figure 7 shows this welded-in drill core.

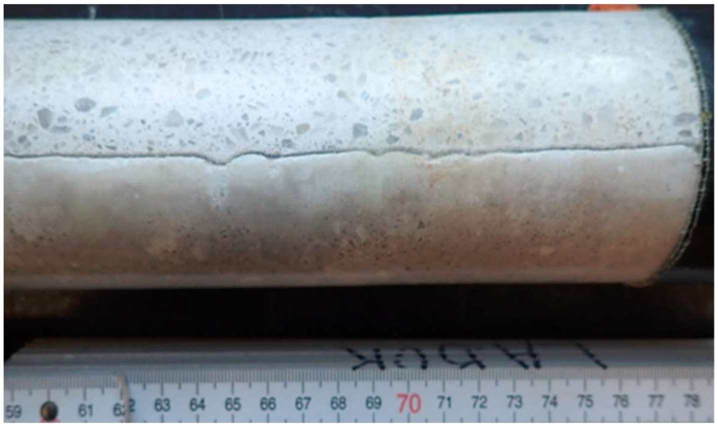

Figure 7 – Drill core from contact area of the text boxes.

In this drill core, the two halves of the core can be clearly distinguished. The lower half visually has a small number of coarser particles, while the upper half contains a large number of coarser particles. Due to the same suspension composition, the same particle size distribution, the same mixing method and time, the same flow rate and the same temperature of the suspension, a sedimentation within the introduced suspension is assumed. This means, that the coarser salt particles sink and the finer salt particles will stay in the upper area of the construction material during the hardening process. In order to prevent sedimentation in the future and to generate a homogeneous construction material, the addition of 8% anhydrite flour was tested in the laboratory. Figure 8 and Figure 9 show the results of the suspension with and without anhydrite flour in direct comparison.

Figure 8 – left: Sorel concrete with anhydrite powder (8%); right: without anhydrite powder.

Figure 9 – left: Sorel concrete without anhydrite powder; right: with anhydrite powder.

Figure 8 shows the concrete with and without anhydrite powder after a waiting time of 24 hours. It can clearly be seen that, in the left sample, no liquid floats, while this is the case in the right sample. The punched holes, that can be seen in the left sample, result from a Vicat test which was performed in order to determine to solidification time. The punched holes in the right sample, on the other hand, cannot be seen. Figure 9 shows the better homogeneity of the construction material mixed with anhydrite powder. The addition of anhydrite flour prevents the occurrence of sedimentation and produces a uniform construction material. For handling reasons, the proportion of anhydrite flour was reduced to 3.9% during concreting. The new mix composition is within the tolerable range of variation [4]. Accordingly, despite the new composition, the new construction material can still run under the name Sorel concrete A1 concrete.

When the dam was built, it was assumed that the nine-hour interruptions between the placement of the batches, due to operational reasons, would not result in notable joints as they have been observed during the between during pretests. However, in the recovery of vertical drill cores from the middle of the dam, an area was discovered where the core pieces did not have a strong connection to each other (Figure 10). The smooth fracture surface can be found in the area where a new batch of the construction material was placed after an eight-hour interruption. Thus, this fracture may be the result of a concreting joint. For further investigation of the concrete joint, another vertical hole was drilled in the edge area. This drill core, however, does not show any separation of the material introduced with 8 hours of interruption.

Figure 10 – Drill core from vertical drilling in the center of the structure - separation surfaces of the upper concreting joint.

Another topic that has been investigated during the project was the temperature of the material during the hydration process. It is known that the temperature may have an influence on the formation of concrete joints. Therefore, sensors were installed at various positions on the salt contour to continuously record the temperature. In addition, a temperature measuring chain was installed in the middle of the dam and recorded the temperature at different heights on the inside of the structure. The measured temperatures at different positions at the formation contour, in the structure and even in the formation are shown as curves in Figure 11.

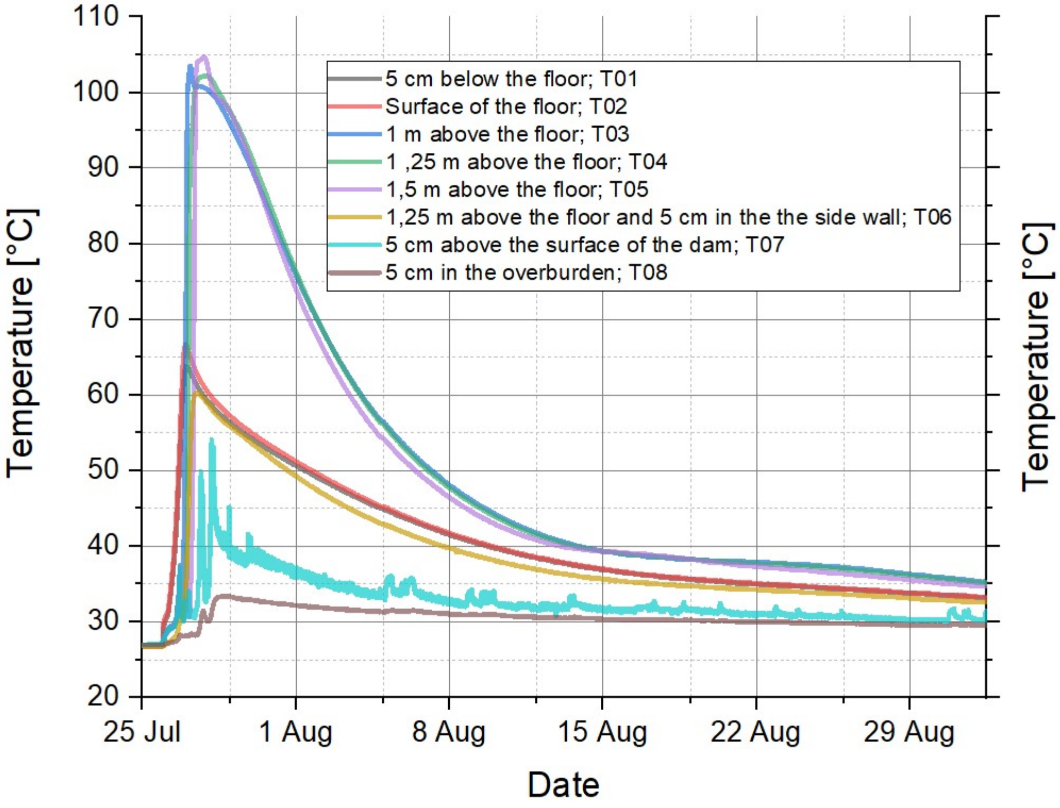

Figure 11 – Temperatures during and after concreting.

Disregarding the measurements in the ridge and 5 cm above the dam surface, the temperature curves can be distinguished into two groups with different maximum temperatures.

- Positioning inside the dam, maximum temperatures approx. 104 °C,
- Contact area sealing material/formation, maximum temperature approx. 67 °C.

These measurements have met the expectations, which were based on experiences, laboratory tests and computer-based models.

With regard to the investigation of the contact zone, it can be noted that the connection of the Sorel concrete to the salt surface is perceived to be good in the areas facing the air (Figure 12). Investigations of drill cores visually confirm a good bond in the peripheral areas of the embankment. In the middle of the embankment, however, there is less bonding of the construction material (Figure 13).

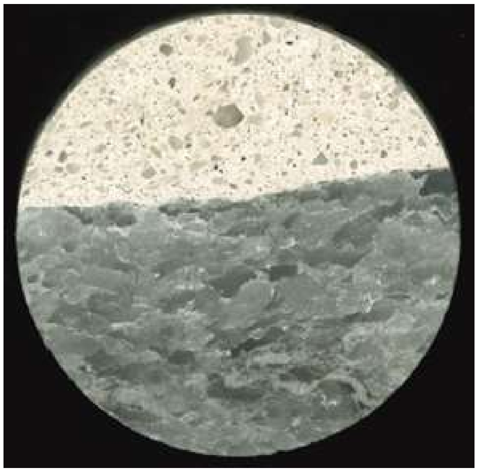

Figure 12 – Drill core from the contact area between the sealing material and the rock with good bonding.

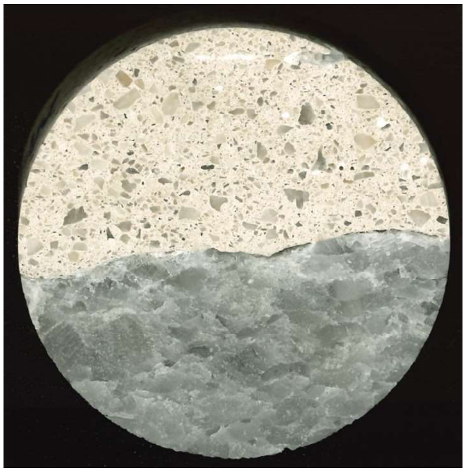

Figure 13 – Drill core from the contact area between the sealing material and the rock with a connection in need of improvement.

Both drill core pieces, which were taken in the Figure 12 and Figure 13 are from the same drill core section from the middle of the bed. The distance between the two samples taken is 12 cm. The drill core from Figure 12 visually shows a good connection of the contact area, while the drill core displayed in Figure 13 on the other hand shows a weak connection based just on the visual impression. When looking at the drill core pieces from the intermediate area of the two sample pieces, a decreasing connection with increasing distance to the face of the dam can be observed. Permeability measurements for the different areas are currently being carried out.

SUMMARY AND OUTLOOK

The objective of the STROEFUN III project was the development of a test concept for the objective, large-scale verification of the fluidic functional safety of installed, safety-relevant drift seals. The concept was successfully implemented and its suitability for the fluidic testing of an installed drift seal was demonstrated. With the time-dependent tests of the structure, a reduction in integral permeability was demonstrated.

By adding anhydrite flour to the original formulation, the sedimentation phenomena was reduced and a homogeneous sealing material produced. Homogeneous bonding of the sealing material to the rock and between concreting layers placed at different times within the structure could not be demonstrated. The cores obtained from the middle of the invert show a local change in the bond between the sealing material and the rock in the contact area between the sealing material and the rock. In the middle of the dam, parallel to the course of the drift, there is a weak connection. The factors influencing this must be investigated.

The incomplete material bond leads to an increase in the integral permeability of the overall structure. The cores originate from an area that was not considered in the determination of the integral permeability. The assumption that this material bond continues through the dam explains the relatively high measured permeability.

Creating fluidically tight barriers is a challenge that must be overcome. A construction material that is partially not bonded to the rock represents a fluidically relevant area. If the target permeability is not achieved, measures must be taken to seal these areas. A measurement system to test a barrier in situ has been successfully tested and is available.

FUNDING NOTE

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