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Grouting Quality of Borehole Heat Exchangers

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ABSTRACT

In Central Europe borehole heat exchanger (BHE) boreholes are usually grouted with cement-based suspensions in order to assure the heat transport between the heat carrier fluid in the BHE pipes and the underground and in order to seal the borehole. The borehole must be sealed for hydrogeological reasons to prevent the intrusion of possibly polluted surface water into the underground and to prevent the connection of different groundwater layers. In Germany several research projects have been carried out in the last years in order to examine the grouting quality of borehole heat exchangers and to determine the main influence factors for the grouting quality. Therefore, test rigs with a height of 6 m were developed in which the grouting process could be visualized. In a second step grouting experiments were done with 30 m deep borehole heat exchangers in a special test rig, that allows a non-destructive removal of the examined borehole heat exchangers. The results concerning the grouting quality that were gained from analysis of the dismantled 6 and 30 m long BHE were compared to the suspension properties of the grouting materials and other factors of the grouting process (e.g. geometry of the borehole, type of mixing machine for the grouting suspension). The suspension properties were measured in laboratory as well as on-site during the grouting process of the tested BHE. Based on these comparisons the main influence factors for the grouting quality have been determined and recommendations for the design and construction of BHEs as well as for the grouting process supervision have been derived. In the latest research projects the examinations described have been extended to the aspect of water exchange between the suspension and the underground. This water exchange can be either due to groundwater flow or due to filtration of the suspension in a water-permeable underground. The results of the research described above is used in national and international technical as well as legislative guidelines and standards like VDI 4640, IEA ECES Annex 27 (Quality Management in Design, Construction and Operation of Borehole Systems, CEN/TC 451 (Water wells and borehole heat exchangers) etc. In this contribution the research methods for determining the main influence factors of BHE grouting quality and the most important outcomes are presented.

1. INTRODUCTION

For some years, society and politics have been striving to convert Germany's energy supply from using fossil and nuclear fuels to a supply based on renewable energies. In 2000, this change was laid down in the Renewable Energy Sources Act (EEG), generally known as the energy transition. A medium-term goal is to generate 40 to 45 % of the total electricity demand from renewable sources by 2025 (BMWi, 2018). More than 50 % of the end energy consumed in Germany is used to generate heat. A successful energy transition therefore requires a heat transition. A combination of different technologies is needed to achieve these goals. One of them is geothermal energy. This energy source offers numerous advantages, as for example base load capability, environmental friendliness, availability, low maintenance requirements and offers also usability for cooling.

At the same time, however, the boreholes for geothermal borehole heat exchangers (BHE) or probes also represent a disturbance of the underground. Drilling through a hydraulic interface can result in a connection and hydraulic short circuit of initially separated aquifers. If aquifers have different hydraulic potentials, groundwater can rise or descend. Due to these altered flow movements, uplifts and subsidence can occur at the ground surface, which in some cases can lead to massive damage of buildings and infrastructure. Furthermore, an inadequate backfilling represents a potential pathway for an intrusion of pollutants into the groundwater.

To prevent all this, in most cases the borehole is filled with a grouting material after the BHEs have been inserted. This is to ensure a proper hydraulic sealing of the BHE borehole and a good thermal connection to the rock.

Unfortunately, in the past there have been several cases of damage due to inadequate backfilling of boreholes. As a result, federal and state authorities have initiated various research projects in order to better understand the processes inside the borehole, to control the technology of geothermal heat utilisation and to guarantee its integrity. Solites was working on this topic in a number of research projects and various reasons for the problem of leaking backfills could be identified. Table 1 lists some of these projects with their main targets.

Table 1: research projects with different targets to optimize quality of backfilling

separation of suspension	filtration	freeze/ thaw- cycling*	bonding to formation/ probe	groundwater flow	chemical resistance*
EWS-tech I & II	QEWS II	QEWS II, and others	EWS plus	EWS-tech II	EWS- tech I & II

* Solites is a member of the joint research project, but has not carried out any own research work on these topics. For a complete presentation, the contents are mentioned, but will not be discussed further in the following.

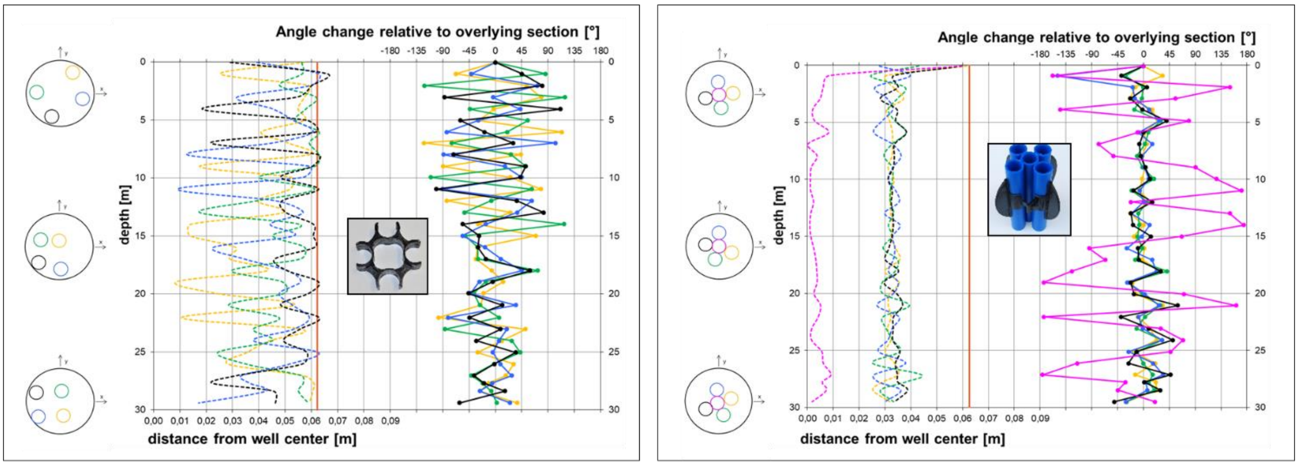
In the following, the contents processed by Solites will be presented in more detail. Projects are running since 2007. Two projects, EWSplus and EWS-tech are finished. They delivered first important insights for the issue of inadequate backfillings of BHEs. The most important outcomes are presented in brief in the following, more detailed information can be found in (Riegger, 2013) and (Riegger et al., 2016). Based on these projects, two following research projects were carryed out, which are ongoing. For these the developed procedures are presented in this paper, as well as first results.

2. COMPLETED PROJECTS

2.1. <u>EWSplus:</u> Investigations for quality assurance of geothermal probes: further development of the borehole heat exchanger- technology (10/2007- 02/2012)

As a part of the EWSplus research project, real scale tests were carried out on non-destructively decomposable geothermal probes for the first time on large scale. For this purpose, a novel test setup was developed which, in addition to a non-destructive dismantling, also permits the determination of the thermal efficiency of the installed geothermal probes. The installation of these real-scale geothermal probes was carried out under construction site conditions in order to ensure the best possible transferability of the test results to BHEs installed in a real borehole.

By investigating 20 real-scale geothermal probes, it was possible to gain significant new insights into the course of the probe tubes in the borehole depending on the use of spacers and centralizers (see fig. 1) as well as into the backfilling quality of geothermal probes with regard to the hydraulic sealing. Incomplete and defective backfilling was found in numerous geothermal probes (fig. 2).



(a) (b)

Figure 1: (a): course of the probes when using spacer, (b): course of the probes when using centralizer

(a) (b)

Figure 2: (a): incomplete backfilling, partially filled with water, (b): porous backfilling

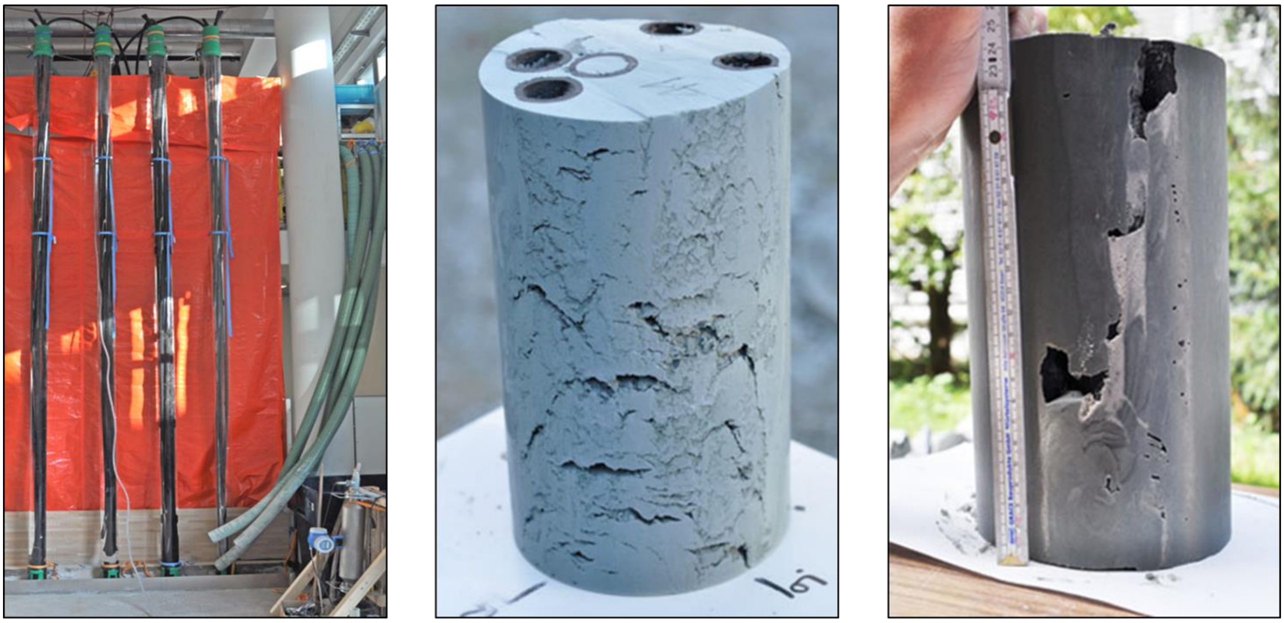
Based on a recording of essential parameters such as density, V- funnel flow and settling of the used backfilling materials and further boundary conditions of the mixing and injection process, it was investigated whether these parameters and boundary conditions correlate with the backfilling qualities found in the disassembled borehole heat exchangers. This could not be proven.

The EWSplus research project raised questions in particular about the backfilling quality of geothermal probes, which were investigated in a follow-up research project in order to contribute to the further development of the BHE technology.

2.2. <u>EWS-tech:</u> Further development of borehole heat exchanger technology: correlation of results of laboratory and large-scale tests (08/2013- 03/2016)

In the EWS-tech joint research project with the project partners Solites, the European Institute for Energy Research (EIFER), the Institute for Applied Geosciences (AGW) and the Materials Testing and Research Institute (MPA Karlsruhe) of the Karlsruhe Institute of Technology (KIT), fundamental questions on the backfilling quality of BHE- probes should be answered. For this purpose, a three-step procedure consisting of laboratory, large-scale and real-scale tests was chosen.

Solites carried out 36 large-scale tests in an above-ground test rig of 6 m height to visualise the backfilling process with the aim to gain an understanding of the backfilling process and the formation of defects. The influence of different parameters on the backfilling quality, for example type and water-solid-ratio (w/s) of the backfilling material, probe type, mixing intensity and mixing time or backfilling speed, was investigated. It could be shown that different types of defects can occur in the backfilling, as e.g. ascent channels, segregation and subsidence (see fig.3).



(a) (b) (c)

Figure 3: (a): large-scale test facility, (b): subsidence in the backfilling, (c): segragation in the backfilling

Three main influencing factors for the formation of defects could be identified: 1) The composition of the grouting material itself. Clear differences in quality between the individual manufacturers could be seen. It was found that the sedimentation rate is suitable as a resilient, independent evaluation criterion for determining a suitable quality of the backfilling suspension. In addition, 2) the mixing technique is crucial for achieving the specified suspension parameters and guaranteeing high-quality backfillings. A colloidal mixer with a high mixing intensity is absolutely required. A mixing technique has also been developed for laboratory mixes, to achieve the same suspension properties as with a construction site mixer. This is decisive for laboratory-scale investigations for statements concerning the application in the field. Furthermore, 3) the position of the probe tubes and installation aids have an influence on the backfilling quality. It has been shown that at locations with a reduced cross-section, as e.g. around centralizers, the formation of a defect is more probable.

With the completion of the two research projects EWSplus and EWS-tech, fundamental findings on behaviour, processes, durability, system permeability and relevant test criteria were gained. Nevertheless, many simplifications and limitations were still existing in the performed tests. The detailed research reports can be found in (Riegger, 2013) and (Riegger et al., 2016)

3. EWS- TECH II

In 2018 the state of Baden-Württemberg has published a quality assurance guideline for geothermal drilling (LQS EWS) (UM, 2018). It contains amongst others an overview of critical groundwater pressure conditions. The EWS-tech II joint research project, with the same partners as in EWS-tech, therefore focuses on investigations on the influence of groundwater flows on the grouting quality of BHEs and sealing of ground water induced flows inside the boreholes. Solites has developed a model to predict the sealing capabilities of groutings as a function of the influencing parameters. To validate and control the model, selected scenarios from the LQS EWS are simulated experimentally in a large-scale test. Thus, the influence of a confined aquifer during backfilling, different groundwater flow velocities and different drilling methods were simulated. In doing so, it was checked whether the predicted sealing of the groundwater flow could be proven in the tests. In the tests groundwater volume flows, grouting materials and backfilling speeds were varied.

3.1 calculation tool for the prediction of the sealing of boreholes

The calculation tool assumes an ideal round shaped, vertical and water-filled borehole in an unpermeable formation. The backfilling is carried out using the contrator method. It can be calculated whether it is possible to seal a borehole that is esposed to a certain groundwater volume flow with a certain suspension volume flow and suspension density. The calculation is based on the method presented in Appendix 3 of the LQS EWS. After entering all relevant parameters, a graph indicates whether the assumed groundwater volume flow can be sealed and how long the procedure takes.

3.2 experimental set up

In order to proof the theoretical considerations of the calculation tool, an experiment was developed which covers all relevant parameters and allows to vary them in a controlled way. The pictures in fig. 4a-c show the individual components of the test facility.

Fig. 4a: The black vertical pipe represents a borehole. At the lower end there is a connection for simulating the groundwater inflow from a confined aquifer, see also fig. 4c. At the upper end a drain for excess suspension or water is available. It can thus be backfilled until the inflow from the simulated lower groundwater inflow has been stopped and no more suspension escapes at the top. The backfilling is carried out in the contractor method using a commercially available colloidal mixer. Characteristic values of the suspension such as density and viscosity are recorded with a coriolis flow meter.

Fig. 4b: The hydrostatic pressure of the groundwater can be adjusted with a working platform. A tank with a defined overflow height is located on the platform for this purpose. Since this height is not changed during the experiment, the effective groundwater pressure remains constant.

Fig. 4c: The simulated groundwater connection in detail. The entering water volume flow is measured with an electromagnetic flow meter (EMF) and controlled by a valve. The water first flows into an over-pipe. Inside is the lower end of the 6 m long pipe for simulating the borehole. Holes are drilled in the borehole pipe in this area, whereby the water flows from the annular of the over-pipe with defined potential into the borehole.

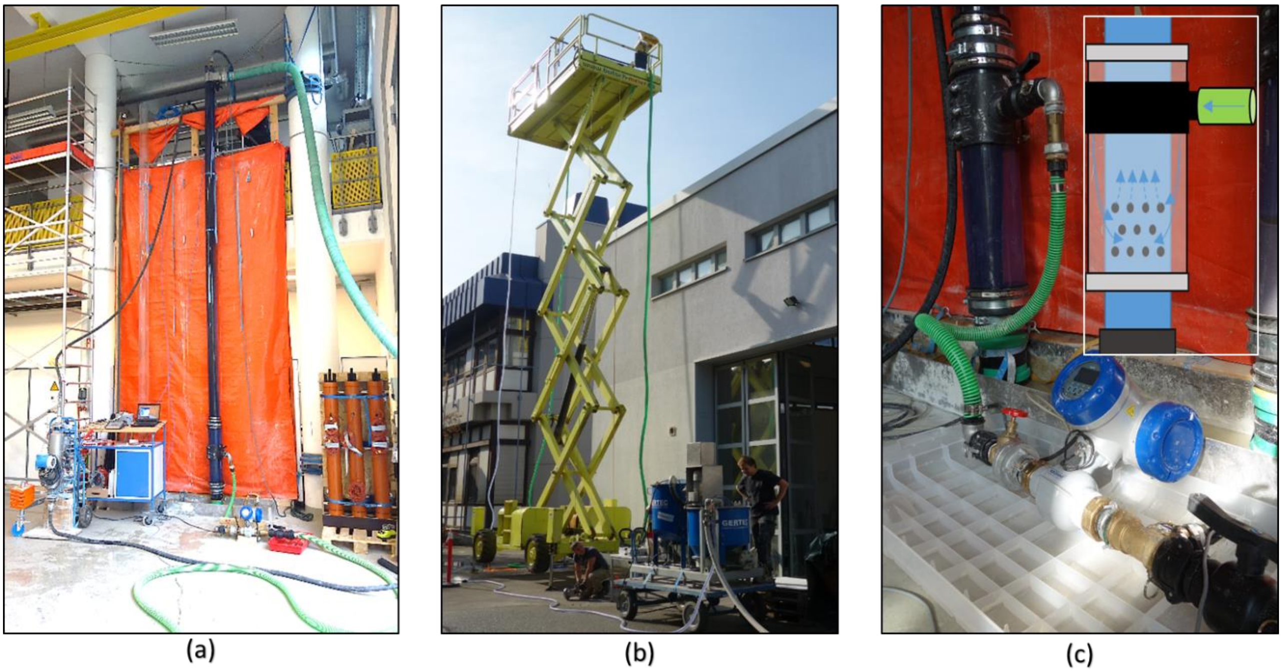


Figure 4: (a): set up with measuring devices, (b): working platform for hydrostatic pressure, (c): ground water connection

So far, three scenarios have been simulated with the experimental set up. One of them is exemplarily discussed in more detail below.

A groundwater volume flow of 40 l/min was set which is classified as critical according to LQS EWS. The pressure potential of the lower ground water connection is 4.85 m above the upper outlet of the pipe. According to the calculation tool for a successful sealing of the inflow a backfilling with a density of >1.85 kg/l is necessary.

In this test, first a suspension density of 1.98 kg/l was used for backfilling. The initial injection volume flow was 38 l/min, see fig. 5 phase 1. Here it could be seen that the groundwater volume flow is reduced, but the amount of suspension introduced was not sufficient to seal the simulated auquifer. A new equilibrium was achieved from the inflow of the groundwater and the reduced density of the injected suspension in the borehole. By increasing the injection volume flow it was possible to seal the aquifer. Fig. 5 shows this process. It can be seen that the measurement data agrees very well with the calculated data.

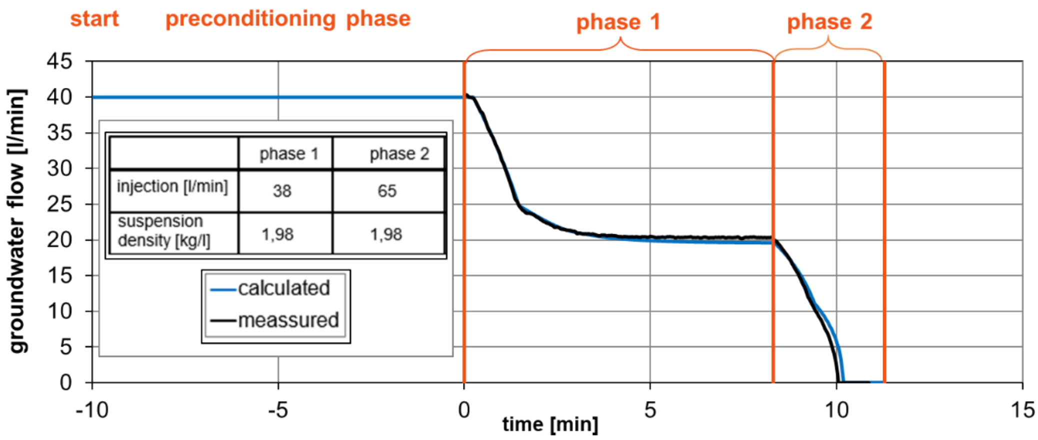


Figure 5: calculated and measured ground water flow during the large-scale experiment

At next the sealing of an aquifer with a low flow velocity and a potential of 2.92 m above the upper aquifer was demonstrated in a test. For this purpose, a low-density grouting material was first injected with a lower injection volume flow. As expected, the sealing was not successful, so that the injection volume flow was increased. But this was not sufficient either. The sealing of the lower aquifer could only be achieved with the injection of another grouting material with a higher density and high volume flow as previvously calculated with the calculation tool.

Conclusion from the previous tests: It could be shown that the calculation tool is able to predict the density and flowrate of the grouting suspension necessary to seal the confined aquifer.

Outlook: To further ensure the reliability of the calculation tool and the requirements of the LQS EWS, at least two further tests with the following scenarios are planned: 1) no critical storey construction, but high groundwater volume flow and 2) backfilling in very critical storey, but with a casing, which is pulled out after the backfilling. Also in this two cases, it should be shown how these conditions can be safely handled and how this procedure can be reliably predicted with the calculation tool.

4. QEWS II

All tests described above were quality tests in impermeable plastic pipes simulating the borehole wall. This theoretically corresponds to an ideal vertical borehole in a very impermeable formation without crevices. It was assumed, that the consistency and composition of the grouting suspension remains the same all over the borehole as it was mixed above ground. This enabled statements and findings about processes within the suspension.

For many geological situations, however, this simplified approach is not sufficient. A borehole heat exchanger is a construction in the geological, heterogeneous underground and interaction between the grouting suspension and the ground hast o be assumed.

In the ongoing QEWS II project, the backfill quality is to be investigated if the backfill suspension can release water into the surrounding formation. Since the driving force of this filtration is a pressure gradient from the suspension to the formation, the investigation of the filtration requires the application of a pressure to the suspension column. At the same time, with this approach a deeper borehole section is imaged than in the plastic pipes previously filled without pressure. A pressure of 4 bar was applied, corresponding to a borehole depth of 22 – 27 m, depending on the density of the grouting material.

The basic question to be answered in this project is: what happens during the filtration of the grouting material in the borehole? What influence do these processes have on the backfill quality? Which properties of the grouting material are neccesary above ground in order to achieve the desired properties in the underground?

The processes regarding the grouting material in the borehole presented in tab. 2 will be investigated within this project:

Table 2: possible consequences of filtration in the borehole (NPI: needle penetration index, SEM: scanning electron microscope)

process		possible effect	evaluation
water loss	→	reduction of defects or bridging / subsidence / holes	visual analysis
segregation	→	unsolidified zones	NPI, density measurement
filter cake	→	hard / resistant / tight backfilling	thin-section, NPI
incomplete hydration of the cement	→	lack of strength, high proportion of capillary pores → high hydraulic permeability	NPI, mercury porosimetry, SEM
bonding to formation and probes?	→	leaking paths	visual analysis

The filtration is influenced by the grouting material and the surrounding formation. The backfilling suspension has a certain density due to its composition of different proportions of solids and water. A pressure force is build up within the suspension column via the resulting pressure gradient, which causes a filtration into the rock in the underlying volumes if the pressure within the suspension column is higher than the pressure in the surrounding formation. The formation pressure depends on the depth and the pressure potential of a possibly existing aquifer. In addition, the permeability of the formation has a crucial influence on the filtration. The larger it is, the more intensive filtration can take place. It can also be assumed that the topography of the borehole has an influence on the filtration, as does the completion of the borehole.

4.1 Theory & pressure cell

In order to approach the question of filtration in the borehole, the issue was first considered theoretically. In a general approach, the filtration can be described by means of the two-phase model. The suspension releases water and consequently builds a filter cake. The release of the filtrate through the filter cake as well as into the surrounding formation can be described mathematically with the Darcy flow. In a pressure cell the filtration pathway runs parallel, in the borehole it is radial.

On a laboratory scale, a pressure cell similar to the apparatus presented in Domes (2015) was first developed. This allows the quantitative investigation and comparison of the filtration behaviour of different grouting materials. The filtrate water and the filter cake thickness can be determined in the ratio per suspension volume, from which the resulting w/s- ratio can be determined after release of the water. In addition, the permeability of the filter cake can be determined with the test setup. Four different grouting materials A-D were investigated, see table 3. The filtration pressure was constant at 7 bar. Sand was used as the filter medium. This was chosen so, that no suspension could penetrate into the grain structure of the sand, but at the same time the filtrate water could flow out unhindered. Each 4.4 l suspension was filled, which corresponds to a filling height of 25 cm. With this volume, a sufficient test duration could be ensured. The end points of the curves in fig. 7 show the time of the complete water release (blow-out).

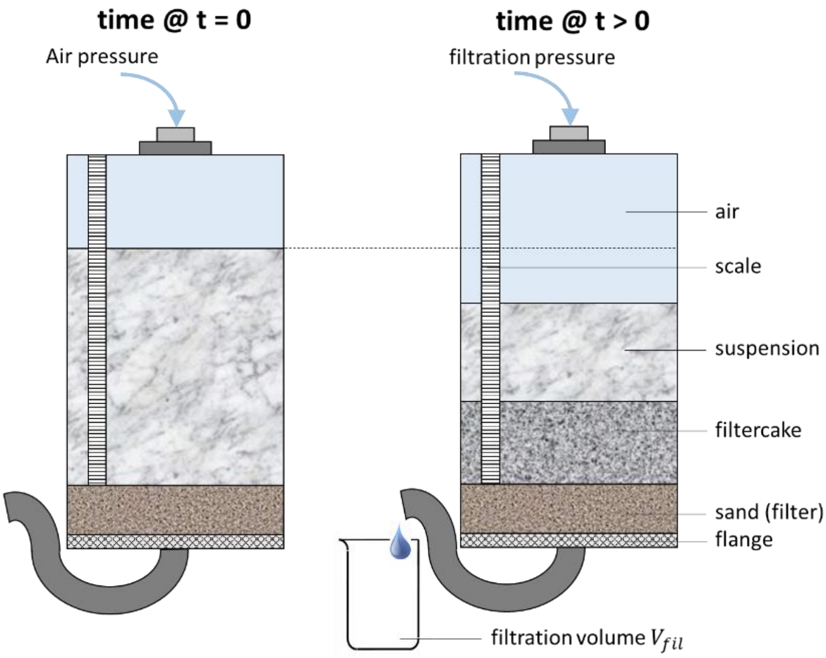


Figure 6: pressure cell before and during filtration

Table 3: outcome from filtration experiments in pressure cell

		A	B	C	D
water/ solid- ratio initial	[-]	0.8	0.82	0.33	0.4
water/solid- ratio final	[-]	0.55	0.35	0.22	0.14
filter cake thickness	[cm]	9.3	14.5	21.3	18.25
cake/ filtrat ratio	[cm³/ml]	1.87	1.56	5.1	2.04
cake/ suspension ratio	[cm³/ml]	0.372	0.58	0.852	0.73
filtrat/ suspension ratio	[ml/ml]	21%	36%	16%	36%
Filtrat /mixing water*	**[ml/ ml]**	**30.7%**	**57.4%**	**39.0%**	**63.8%**
settlement (laboratory)	[%]	1%	4%	0.3%	4%
permeability cake	**[m/s]**	**2.36E-08**	**5.93E-08**	**5.37E-08**	**3.60E-07**

* initial amount of water used for mixing the grouting suspension

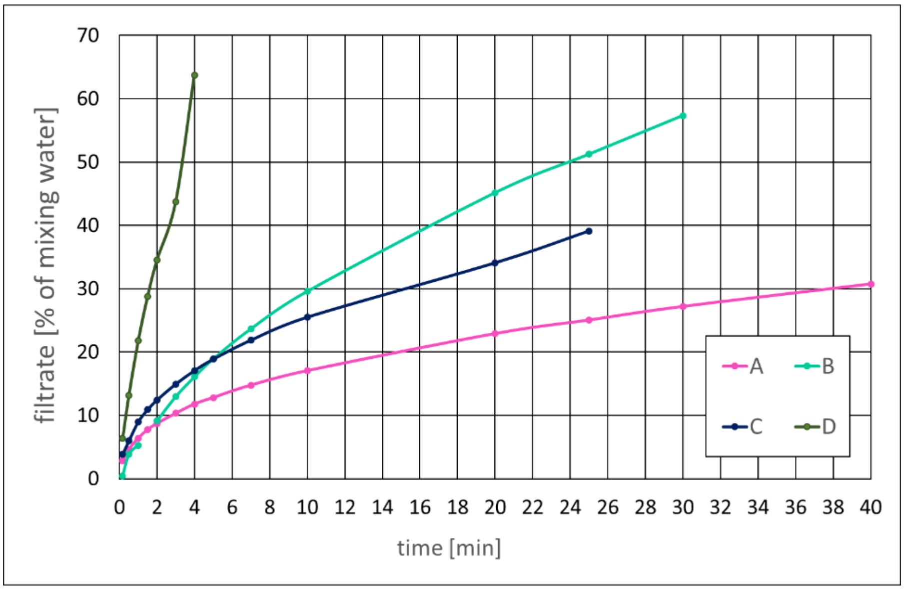


Figure 7: filtrate as percentage from mixing water during the filtration experiment in the pressure cell

The filtration behaviour of the grouting materials is very individual (fig. 7). It is difficult to identify general trends. One is that with an increasing w/s- ratio of the suspension, thinner filter cakes are formed, both in absolute numbers and in relation to the volume of filtrate water pressed off. However, it cannot be recognized that the absolute filtrate water output also increases with an increasing w/s-ratio. Instead, it was observed that in grouting materials with a low w/s-ratio, a blow-out or water breakthrough occurs earlier. Channel structures are formed within the filter cake through which air or water can flow unhindered. In addition, the w/s-ratio of the remaining suspension or the filter cake decreases with an increasing filter cake height. In a grouting material with a low initial w/s-ratio, more water relative to the mixing water was pressed off. It should be checked whether there is still sufficient water for complete hydration if the final w/s ratio is undershot. More precise information is not possible, as the composition of the grouting materials, and thus the cement content in the material, is subject to the manufacturer's internal knowledge.

With these initial tests, a deeper understanding of the behaviour of the grouting materials was created. Above all, it can be seen that the behaviour is very individual. The details can provide valuable information to ensure the required quality of borehole fillings. However, the occurrence of defects etc. can only be investigated and predicted in a large-scale test. The theoretical consideration of filtration in the borehole hereby shows some differences and uncertainties compared to filtration in the pressure cell:

- Static or dynamic filtration (Lutz (2018)): depending on the backfilling process, with effects on the abrasion of the filter cake and depth filtration in the formation during filling
- Pressure regime: increasing pressure as a result of the ascent of suspension column
- Radial conditions: decrease in filter area with increasing filter cake thickness
- Fissured surrounding, unevenly permeable filter medium (= formation) leads to inhomogeneous water release and thus to inhomogeneous backfilling.
- Duration of backfilling: hydration may already begin during backfilling process
- Possible segregation and subsidence due to the height of the column

Some of these aspects were incorporated into the developed real-scale test, described in the following section.

4.2 Real-scale test

Based on the previous laboratory tests, a multi-shell real-scale test setup was developed, which is pressure-stable up to a maximum pressure of 7 bar. This can be used to simulate a 3 to 6 m deep BHE borehole in an artificial formation (fig. 8). The aim was to develop a test setup that has the same structure for different formations and to allow for the measurement of the amount of filtrate water released. For the simulation of a permeable formation a fine sand is used as in the laboratory tests carried out before. In order to reproduce a low permeability formation, a deep drilling cement s used instead of fine sand. During the test, the borehole filled with backfilling suspension is successively subjected to increasing pressure at the pressure-tight wellhead thus to simulate the increase in pressure of the backfilling suspension column in a deeper borehole. In the test series described, a maximum pressure of four bar is maintained for a defined time. During the entire test, the amount of filtrate water discharged from the initially saturated formation is measured.

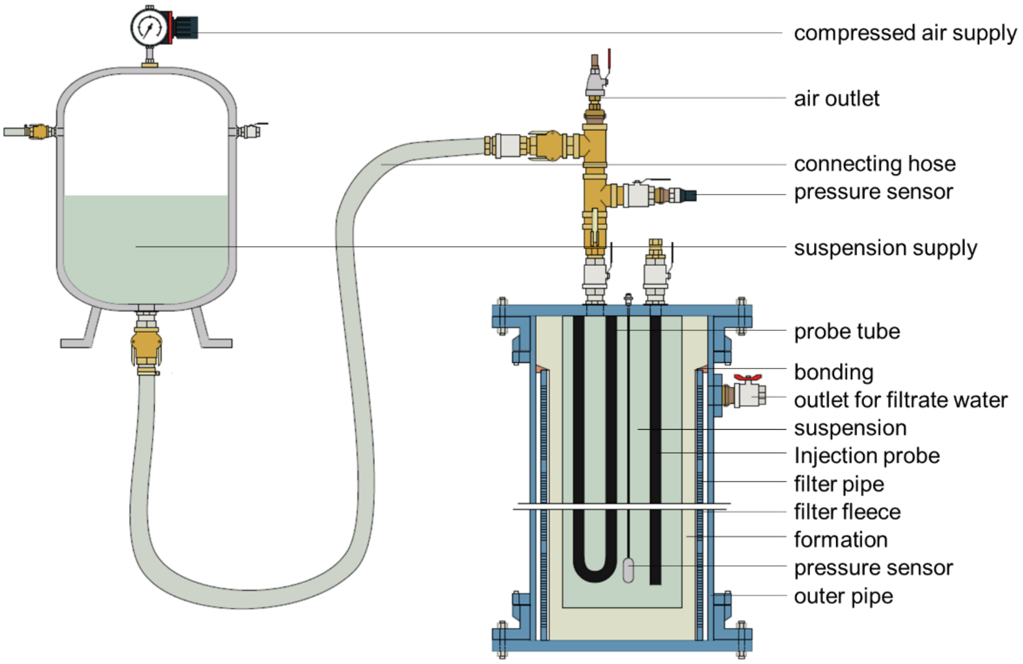


Figure 8: Design of the dismountable real-scale filtration experiment for the analysis of BHE backfillings

4.3 Investigations & Results

In order to investigate various influences and boundary conditions in addition to the filtration itself, eigth different experiments are performed. In these experiments, two different grouting materials are used, whose filtration behaviours are investigated in four experiments each. Each grouting material is subject to a series of tests in permeable sand formation and low permeable cement formation in setups with BHE pipes and without BHE pipes. Two reference tests in impermeable PE pipes provide comparability with the former tests in the EWSplus and EWS-tech projects without filtration.

So far the tests 1- 4 and the reference test 1 with grouting material 1 could be carried out.

The evaluation of the tests is based on the temporal course of the determined filtrate water quantity and the quality of the hardened backfill material, which was analysed after hardening and dismantling of the test formation. Analogous to the pressure cell tests, the formation of a filter cake was also clearly visible in the large test stand after the end of the test (i.e. after a filtration period of up to two hours). While in the filtration cell tests the filter cake was formed on a flat surface, in the real scale tests the filter cake was formed on the borehole wall with still unfiltered suspension in the centre of the borehole. Fig. 9 shows the typical course of a filtration curve for the BHE backfill introduced in a permeable formation. The release of the filtrate water from the suspension into the permeable formation begins at the start of pressurisation. The increasing pressure at the wellhead simulates the increasing hydrostatic pressure during the filling process of a BHE. Simultaneously to the filtrate water release, a filter cake forms on the borehole wall whose hydraulic permeability decreases with increasing thickness and thus the filtrate water release is strongly reduced after only two minutes, despite further increasing pressure.

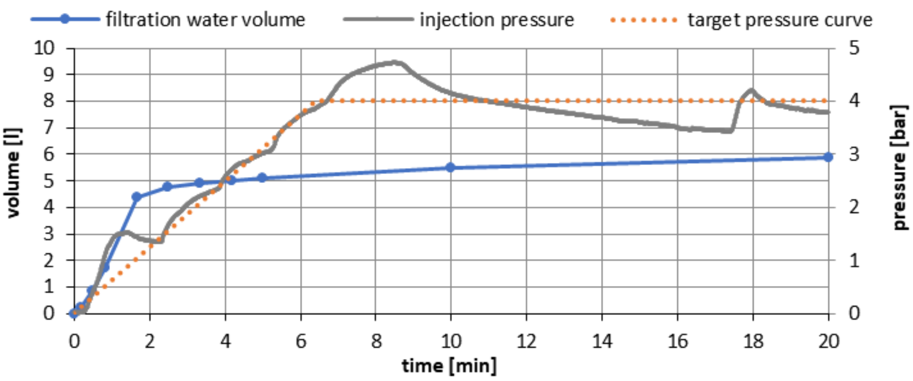


Figure 9: Filtration experiment of a real-scale test with sand formation and a maximum target pressure of 4 bar

A visual inspection of the cured BHE backfill shows that the backfill is externally intact without any visually detectable quality defects (fig. 10 left). The cross-section, however, indicates that the backfill is not homogeneous, but shows areas with filter cakes and segregations (fig. 10 right).

Often the differences between filter cake and segregation range are not as obvious as shown in fig. 10. The measurement of the penetration resistance with a needle penetrometer is a possibility for further analysis. In many borehole sections this analysis method was able to detect radial differences along the borehole cross-section (fig. 11). This indicates that the backfill material at the borehole wall has a higher uniaxial compressive strength, which is probably due to the formation of a filter cake as a result of filtration and segregation processes. Particles have accumulated there, compacted and thus created a denser structure. The measured values in the upper area of the backfill often show the largest spectrum. With increasing depth, a more homogeneous distribution of the penetration resistance becomes apparent (fig. 11).

Figure 10: left: dismantled backfilling built in sand formation. right: selected cross-section of the same backfilling.

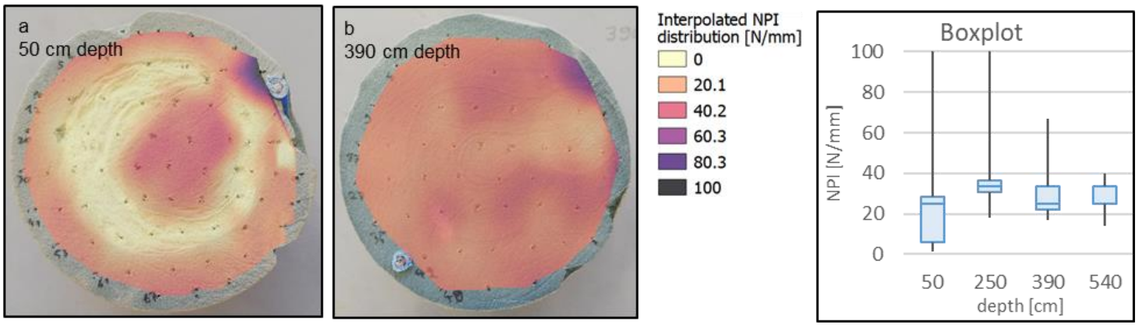


Figure 11: left: NPI of the cross-sections of samples from 50 cm (a) and 390 cm (b) depth of an artificial BHE backfilling in sand formation. right: NPI box plot of the same backfilling in 4 different depths. The distribution of the measured NPI values becomes smaller, the deeper the sample was taken.

Mercury porosimetry enables the small-scale investigation of the distribution of the pore opening width. The investigations show that the pore size distribution of the filter cake is similar to that of an undisturbed blind sample (not backfilled), whereby the pore volume fraction in the measured range is significantly lower in the filter cake. For segregated areas, the pore size distribution shifts towards pores with larger opening widths which then lie in the range of hydraulic efficiency (fig 12).

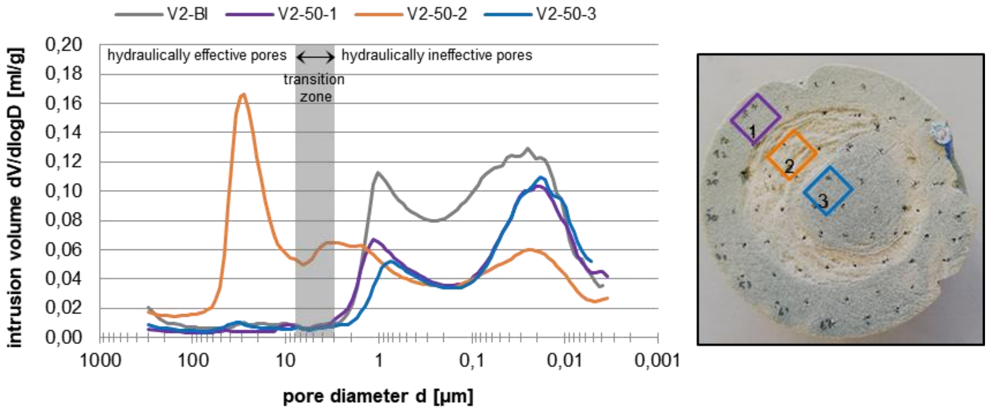


Figure 12: Pore size distribution of the cross-section sample from 50 cm depth of an artificial BHE filling produced in sand formation. Samples V2-50-1,-2,-3 from positions 1, 2 and 3 of the sample on the right. Blind sample V2-Bl was taken from the same material, which was not backfilled and therefore is used as reference for an unfiltered grouting material.

Table 4: water content and dry densities from selected samples V2-50 and V2-390 with cross-sections from 50 and 390 cm depth of an artificial BHE filling produced in sand formation.

sample no.	water content [%]	dry density [g/cm³]
V2_50_1	6,85	1,91
V2_50_2	6,60	1,82
V2_50_3	8,38	1,90
V2_390_1	8,99	1,85
V2_390_2	8,53	1,85
V2_390_3	9,57	1,84

A comparison of the properties of the filter cake and the segregation area with respect to the unfiltered area in the BHE filling or blank samples reveals the following trends:
▪ The filter cake has a higher NPI, higher density, less pore volume and lower water content (see tab. 4)
▪ The demixing area has a lower NPI, lower density and larger pores.

With increasing depth, the following trend can be seen:
▪ A higher homogeneity in the cross-section profile, thus reduced delimitation of filter cake and segregation area
▪ Higher NPI, lower dry density, higher water content

Comparison between permeable formations and low permeability formations:
▪ Filtration is more pronounced with higher permeability.
▪ All differences between filter cake, unfiltered area and segregation area are more prominent with higher permeability of formation.

5 CONCLUSION

Quality defects such as those known from the former EWSplus and EWS-tech projects presented in section 2 do not occur in the filtration experiments of the QEWS II filtration setup. By releasing the filtrate water to the surrounding geology, defects, ascent channels and subsidence are prevented in the experiments performed.

In summary, the QEWS II tests carried out show, that the large-scale test setup developed offers the possibility of realistic investigation of the filtration behaviour of BHE backfilling materials. It is able to show the differences in the filtration behaviour and in the properties of the cured grouting materials resulting for different boundary conditions, such as different formations, pressures and grouting suspensions. Conclusions on the properties of the cured backfilling can be drawn only in conjunction from all test methods used. After the visual examination of the reconstructed BHE, sampling with a needle penetrometer is recommended. The needle penetrometer test provides reliable information about the NPI from which the uniaxial compressive strength can be estimated. Based on the large-scale tests still to be carried out, essential statements on the borehole integrity of BHE can be derived taking into account the filtration behaviour.

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