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High-density bimodal bentonite blends for hydraulic sealings at the Ibbenbüren coalmine

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ABSTRACT: The two high-pressure water-retaining dams at the Ibbenbüren coalmine in Münsterland (Germany) have to perform reliably under the induced tension caused by further exploitation of the current mining area. The load-bearing and the sealing functions of the new barriers were separated and new sealing materials were developed. An innovative multilayer sealing system of bentonite and sandwiched equipotential layers (SANDWICH) supporting homogeneous swelling and sealing, independent of formation water (Nüesch *et al.*, 2002), was applied in this project. A testing program of strain-controlled swelling pressure tests on compacted bentonite specimens and on a bentonite/sand mixture was conducted to ensure an adequate potential for swelling-pressure development.

The measurements under constant volume for dry densities between 1.45 g/cm³ and 1.67 g/cm³ showed an evolving swelling pressure between 1.04 and 1.8 MPa for 100% bentonite samples. Strain-controlled oedometer tests for zero strain and step-wise applied strain up to 2% revealed that a sufficient magnitude of swelling pressure existed at maximum applied strain.

KEYWORDS: Swelling pressure, hydraulic sealing, bentonite, SANDWICH system, equipotential layer, self-compacting bimodal-blend.

The company ‘RAG Anthrazit Ibbenbüren GmbH’ has developed the exploitation area known as ‘Beustfeld’ at depths of 1200–1400 m in northern Münsterland, Germany. The planned exploitation affects two existing high-pressure water dams. Therefore, two new substituting barriers located at the Bockraden shaft in a depth of ~270 m were designed.

The mining area of the Ibbenbüren pit is separated into eastern and western parts. The western part was closed down in 1979 and has been flooded since then. The western and the eastern areas were connected by two gateways, the crosscut on the third floor and the airway of seam Glücksburg (Fig. 1). To prevent water flow from the western area towards the eastern area, two high-pressure water dams were installed in the connecting crosscuts during the 1980s. Dam 59 is located in the airway of seam ‘Glücksburg’ and dam 71 is located below the third floor.

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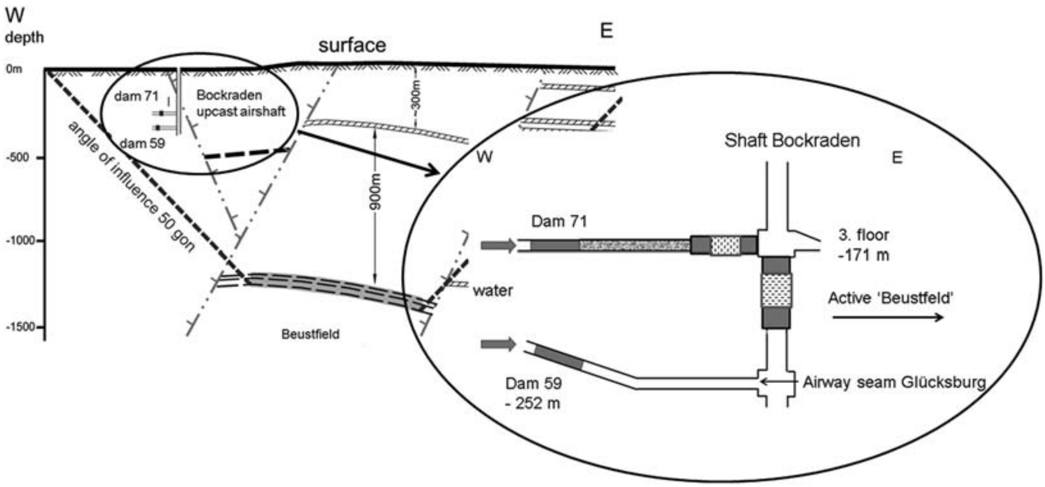

FIG. 1. Section of the west–east profile of the 'Beustfeld' in the Ibbenbüren coalmine with the location of old dam 59 and dam 71 situated within the angle of influence (50 gon, a surveyor's term which corresponds to 45°).

Further exploitation of the 'Beustfeld' will end in 2018. The Bockraden up-cast airshaft lies in the influence area of the exploitation. The shaft connects the surface with the third floor in the mine at a depth of 270 m. The total depth of the shaft is 391 m. The shaft below the third floor was flooded.

Initially, the existing high-pressure dams 59 and 71 inhibited the water inflow towards the east under normal site-working conditions. With the proposed exploitation at a depth of 1200 m, the existing dams may lose their functionality due to induced tension or strain relaxation. Numerical simulation studies showed that cracks up to 2 mm wide are possible due to coal exploitation (Goerke-Mallet & Clostermann, 2011). In particular, the dam pipe could lead to increased tensions in dam 59. Therefore, substituting dams had to be installed. The new dams should be able to absorb the tensions induced by the exploitation (Kunz *et al.*, 2014). For dam 59, the substitute was placed in the Bockraden shaft and the replacement for dam 71 was placed on the third floor of the Bockraden underground mine.

In the design of the new dams, the static or load-bearing function was separated from the sealing function. For reliable performance of the sealing system, the reduced hydraulic conductivity or resulting

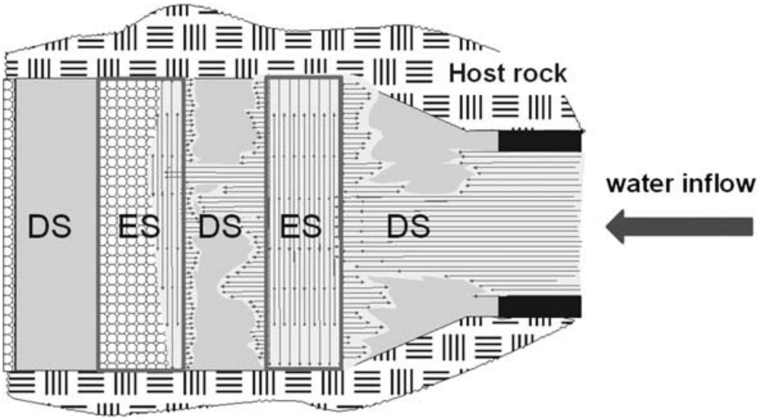

FIG. 2. Hydraulic sealing system, SANDWICH, of bentonite (DS) and silty/sandy (ES) materials to enhance homogenous saturation and swelling.

hydraulic conductivity should be <1E–9 m/s under the conditions of plastic deformation and induced volumetric strain of at least 1%. To fulfil site-specific requirements, the sealing had to undergo homogenous saturation and swelling to a swelling pressure of 0.5–3 MPa. Furthermore, it had to be proven that the new sealing element could cope with the expected volumetric strain caused by exploitation.

The hydraulic sealing element of drift and shaft-sealing systems in deep geological disposal systems or underground mining pits is commonly made up of a monolithic construction of compacted bentonite or a compacted bentonite/sand mixture. Inevitable inhomogeneity developed during construction and/or a sudden fluid entry with high hydraulic pressure might cause preferential pathways or even fracture of the hydraulic sealing, enhancing water flow. In a large-scale field test of a bentonite sealing construction, pathways occurred at the top and bottom of the construction (Sitz *et al.*, 2003). Therefore, in the new dams, abutments serve as load-bearing elements and the SANDWICH-system (Nüesch *et al.*, 2002) as the sealing. The SANDWICH sealing system combines bentonite sealing segments (DS) of low hydraulic conductivity (1E–11 to 1E–13 m/s) intersected by equipotential segments (ES) characterized by a hydraulic conductivity at least 10 times greater than that of the bentonite used (Nüesch *et al.*, 2002).

The ES inhibit inhomogeneous moisture transport through the bentonite and thus prevent inhomogeneous swelling of the hydraulic barrier. Water penetrating from the interface between host rock and sealing system or water fingering within the sealing system is evenly distributed within an ES and builds up a new homogeneous potential surface for the following DS. This supports a more homogeneous swelling process (Emmerich *et al.*, 2009). Appropriate installation and material properties of ES and DS are able to enhance the absorption of volumetric strain or regulation of swelling pressure in the sealing system.

The sealing element has to be constructed by a self-compacting blend with the minimum possible emplacement time without interruptions. Failure under the above-mentioned emplacement conditions may cause spontaneous swelling due to significant site-specific water inflow. As a consequence of high water inflow, a very slow-swelling sealing material was used to avoid spontaneous swelling and lower densities during emplacement.

Compacted bentonite is favoured as a buffer of sealing material in nuclear-waste repositories. Performance measured as swelling pressure is not only influenced by dry density and interlayer occupancy of the smectite in the bentonite (Bucher, 1986; Bucher & Müller-Vonmoos, 1987; Butz, 2002; Herbert & Moog, 2002; Kennedy *et al.*, 2003 Baille *et al.*, 2010) but also by temperature, hydraulic pressure and chemistry of the groundwater. The influence of steam or cement was also examined (Oscarson & Dixon, 1989; Madsen, 1998). For repository conditions, a timescale of ~1 Myr is required. Due to self-healing, swelling capacity and the very low permeability, water transport is retarded. For highly compacted bentonites with final dry densities of up to 2.0 g/cm³, the swelling pressure increases to 40 MPa (Bucher, 1986; Madsen, 1998). Agus (2005) measured swelling pressures of a calcium bentonite of 2–5 MPa for bentonite dry densities of ~1.6–1.7 g/cm³ and in the lower region, dry densities of 1.1–1.24 g/cm³ and swelling pressures of 100–385 kPa. To obtain dry densities of >1.6 g/cm³, a significant technical effort is required. Bentonite bricks have to be produced and the bricks can only be installed manually. They cannot be used for a quick and self-compacting installation of sealing in a shaft. The sensibility of compacted dry bentonite bricks against moisture was also a criterion of rejection. These well known concepts (Gattermann, 1998) are only suitable for dry host rocks, especially in formations with high salinity.

Therefore, granular bentonites with very little water content were used as backfill material added to bentonite pellets or briquettes. Kennedy *et al.* (2003) obtained granular backfill material with a density of 1.48 g/cm³ and an average moisture content of 3.6%. Sitz *et al.* (2003) used a binary mixture of bentonite briquettes with granular backfilling material for the shaft in Salzdetfurth, modified after Naundorf & Wollenberg (1992). Martino *et al.* (2011) reported an *in situ* compacted bentonite clay-sand mixture in a shaft where a mixture of 40% bentonite with 60% sand was compacted in 5 cm layers using conventional hand-operated compaction equipment. An average dry density of 1.81 g/cm³ was achieved. The density was calculated to correspond to an effective montmorillonite dry density of ~1.03 g/cm³. In the RESAEL project (Van Geet *et al.*, 2009) the shaft was filled with a mixture of 50% bentonite pellets and 50% bentonite powder. The bulk density achieved in the compacted region was 1.54 g/cm³ for the mixture (1.45 g/cm³ dry density, respectively) and the bulk density without compaction was 1.38 g/cm³ (1.30 g/cm³ dry density, respectively). The effective stresses were 450–700 kPa and the hydraulic conductivity of the sealing material was in the order of 1E–12 m/s.

For the first time, in the Bockraden shaft in Ibbenbüren, a self-compacting bimodal bentonite blend was emplaced that did not need to be compacted using conventional methods. Self-compacting materials had to be used because conventional compacting machines such as vibration-plate compactors are not approved in underground coalmines for safety reasons.

The present study describes the development of the high-density bimodal bentonite blend that is suitable for installation in SANDWICH sealing systems under water inflow during emplacement. For the development of the material, laboratory and *in situ* tests were performed. The determination of swelling pressures, the hydraulic conductivity, the evaluation of the optimal blend and testing of the pneumatic emplacement methods were the focus of the current project.

MATERIALS FOR THE SANDWICH SYSTEM

Equipotential material

Different materials were used for the ES in the shaft and the gateway. In the shaft, a capillary rising of 0.5 m corresponding to the thickness of the horizontal layers was sufficient. A fine sand (H35S, Quarzwerke GmbH Haltern) with a bulk density of 1.59 g/cm³, characterized by a capillary rising height of >50 cm after 1.3 days, was installed.

In the gateway the segments were placed vertically and a capillary rising of at least 3.5 m was required. To achieve such capillary rising in the gateway, a four-component mixture was used. Fine-grained sand (N45, Nivelstein) restored the mechanical stability and filling the pore space between the sand grains with a silty mineral mixture ensured the capillary rising properties. The technical mineral mixture consisted of a quartz feldspar mixture (FS700, Amberger Kaolinwerke), powdered lacustrine limestone (BMK Heilbronn) and clay, consisting mainly of illite (Arginotec GI, B+M Nottenkämper). A capillary rising height of 3.5 m occurred after ~200 days for the mixture with a bulk density of 1.63 g/cm³ and a starting water content of ~1.3%. The measured hydraulic conductivity of the material used was 6E–9 m/s. An optimal proctor density of 1.76 g/cm³ appeared at a water content of ~14% (referred to as dry mass). The swelling pressure in the sealing segment (DS) would be greatest for constant-volume conditions. Therefore, the *in situ* density, and thus the stiffness of the adjacent equipotential material (ES), had to be as great as possible in order to avoid a condition where the volume was not constant and a subsequent decrease in exerted swelling pressure by the sealing segment (DS) occurred. Calculations described briefly below prove that at least 97% of the proctor density was necessary for the usability of the dams.

Sealing material

A bentonite blend consisting of two Na-activated bentonites from Westerwald (Wimpfsfeld III pit, Arborn, Hessen, Germany) and Milos (Greece) was used for the production of bentonite pellets. The montmorillonite content in the blend was ~70%.

For the bimodal blend of bentonite and quartz sand, fire-dried quartz sand from Haltern was chosen as the best-performance filler. The quartz sand H35S consisted of 99% SiO_2 with an average grain size of 0.17 mm and a theoretical specific surface area of 137 cm²/g.

Methods and general parameters. The water content of the bentonite, with reference to the dry mass of the blend, was adjusted to 28% in order to achieve good extrusion properties. After the extrusion process, the pellets were dried carefully to 14–16% residual water content. The measured water uptake (DIN 18132) of the extruded bentonite pellets was 120% after 16 min and 370% after 24 h, both with reference to the dry mass. The cation exchange capacity (CEC) was determined by the copper triethylenetetramine method (Meier & Kahr, 1999; Wolters *et al.*, 2009). The CEC of the blend was 60 meq/100 g. The swelling of the pellets was measured according to an internal industrial standard method in a 500 mL glass cup. The swelling capacity of 100 g pellets ranged between 300 mL and 400 mL.

In order to prepare samples in accordance with the water-permeability tests (DIN 18130), the bimodal blend was stirred in a propeller mixer and poured subsequently into a sample container with latex lining. The material was then adjusted to densities of 1.70 g/cm³ and 1.75 g/cm³. After 2 months, the optimized sample with a density of 1.75 g/cm³ showed a hydraulic conductivity of 4E–12 m/s.

The swelling pressure of the bentonite was determined with a high-pressure oedometer. A detailed description of the device used was given by Baille *et al.* (2010). The compacted bentonite samples were hydrated with water from Ibbenbüren, sampled on the third floor in order to obtain the same conditions as in the Bockraden shaft. Prior to testing, the bentonite powder was stored for at least 2 weeks in a desiccator

TABLE 1. Swelling-pressure testing program of 100% Westerwald/Milos bentonite (water content with reference to dry mass).

Sample/test	Boundary condition (volume change)		Dry density, ρ_d [g/cm³]	Initial water content [%]
	$\Delta V = 0$	ΔV		
QV01a	X	–	1.26	15.21
QV02a	X	X	1.41	14.40
QV02b	X	–	1.45	18.68
QV03a	X	X	1.64	17.50
QV03b	X	–	1.58	18.78
QV03c	X	–	1.67	18.68

(X = performed tests).

with $MgNO_3$ to obtain an adsorbed water content of 13.5–17.5%. The samples with different dry densities were compacted statically in the oedometer ring. The diameter of the ring was 5 cm and the sample height was 1.5 cm. The specimen size did not allow for testing of the bentonite pellets/sand mixture; therefore, the tests were performed using bentonite powder. In a first step, the specimen was hydrated with the fluid under strain-controlled conditions (zero strain) and the swelling pressure was monitored with time. When the swelling pressure reached equilibrium, in a second step, the restraint was lifted to allow a predetermined strain. The specimen was allowed to increase its volume upon further saturation under stress-controlled conditions (zero stress) until a strain-controlled condition (zero strain) was attained again. Step 2 was repeated for predetermined strains 0.5% to 2%. Tables 1 and 2 show the measurement conditions for the bentonite and the bentonite/sand mixture. As shown earlier, the swelling pressure of a bentonite/sand mixture was mainly determined by the effective bentonite dry density in the mixture. A unique swelling pressure-dry density relationship exists for bentonite/sand mixtures of different ratios, where the swelling pressure refers to the dry density of the bentonite fraction rather than to the dry density of the mixture (Agus, 2005; Wang *et al.*, 2013). Therefore, the swelling pressures were performed on pure bentonite samples for varying dry densities. This enabled the prediction of swelling pressure of bentonite/sand mixtures. Two tests on bentonite/sand mixtures were performed for verification purposes.

Swelling-pressure test results of the bimodal bentonite blend.

In order to prove the functionality of the dams, the following swelling-pressure tests were performed. First, in the shaft and the gateway a constant volume was assumed at the beginning of the exploitation when

TABLE 2. Swelling-pressure testing program of bentonite/sand mixture (water content with reference to dry mass).

Sample/test	Boundary condition (volume change)		Mixture dry density, $\rho_{d,M}$ [g/cm³]	Bentonite dry density, $\rho_{d,B}$ [g/cm³]	Water content, bentonite [%]	Water content, mixture [%]
	$\Delta V = 0$	ΔV				
QV04_BS	X	–	1.60	1.26	15.29	9.17
QV05_BS	X	–	1.50	1.26	15.30	10.70

(X = performed tests).

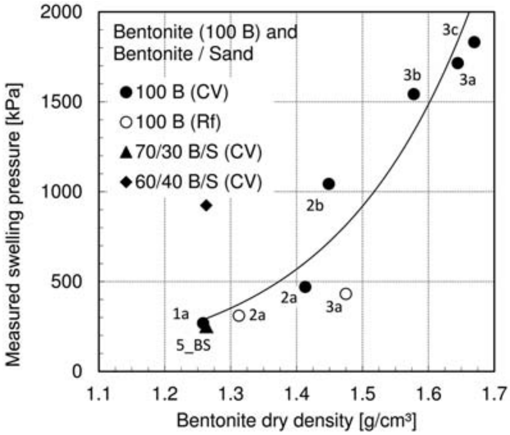

FIG. 3. Measured swelling pressure vs. bentonite dry density for the constant volume (CV) tests and the final state of the relaxation tests (Rf) of the bentonite specimens (100 B) and the bentonite/sand mixtures.

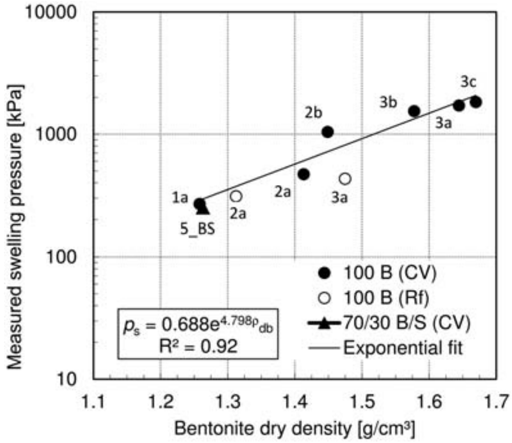

FIG. 4. Swelling pressure vs. bentonite dry density data points and established relationship based on the 100B specimens.

the sealing was encapsulated between the abutments. The maximum swelling potential was measured as a function of the dry density and constant volume (CV) of pure bentonite (Fig. 3). Secondly, numerical simulations for the old dams showed that cracks and fissures of >1 mm were likely to occur due to exploitation. Therefore, the new dams had to resist a strain of ~2% due to the exploitation. This means that the existence of a sufficient magnitude of swelling pressure after induced strain, i.e. induced volume increase of the sealing element, had to be proven. Thus, a step-wise applied strain (referred to as Rf) up to 2% was allowed for two samples after the constant-volume swelling-pressure development reached equilibrium. Thirdly, the swelling pressure of a bentonite/sand mixture was investigated to enable recalculation of the remaining swelling pressure of the installed self-compacting bimodal blend.

The specimens of pure bentonite had initial dry densities from 1.26 g/cm³ up to 1.67 g/cm³ and water contents of 14.4 to 18.8%. The range of 1.26 g/cm³ to 1.67 g/cm³ corresponded to the densities obtained by the pneumatic tests of bentonite pellets with granular bentonite and a bentonite-sand mixture.

The swelling pressure rose with increasing density of the bentonite (Fig. 3). The filled symbols are the samples under constant-volume (CV) conditions ($\Delta V = 0$). The swelling pressure of the bentonite was 269 kPa at a dry density of 1.26 g/cm³ and increased to 1832 kPa for a dry density of 1.67 g/cm³. This relation was used for an exponential fit to calculate the swelling pressure for any given dry density of the Westerwald/Milos bentonite (Fig. 4). Swelling pressure, p_s, of the bentonite in relation to the dry density ($\rho_{d,B}$) can be determined with the following approximation:

$$p_s = 0.688 \cdot e^{4{,}798\rho_{d,B}} \left(R^2 = 0.92\right) \tag{1}$$

After the swelling at CV conditions, a stepwise relaxation corresponding to the strain induced by the planned exploitation was applied for samples 2a and 3a. Open symbols represent the final state at the end of the last applied relaxation phase (Rf). For specimens 2a and 3a, the final applied strains were 2.0% and

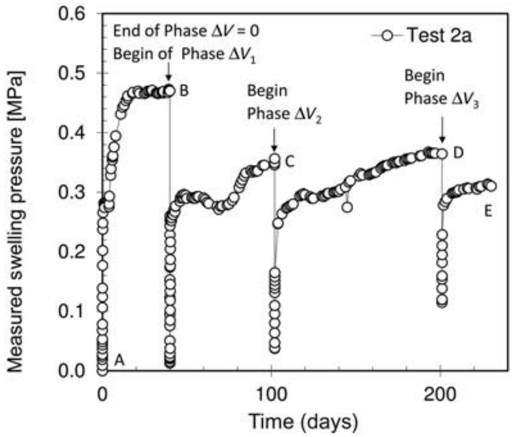

FIG. 5. Swelling pressure–time plot for the constant volume and relaxation test stages of specimen 2a.

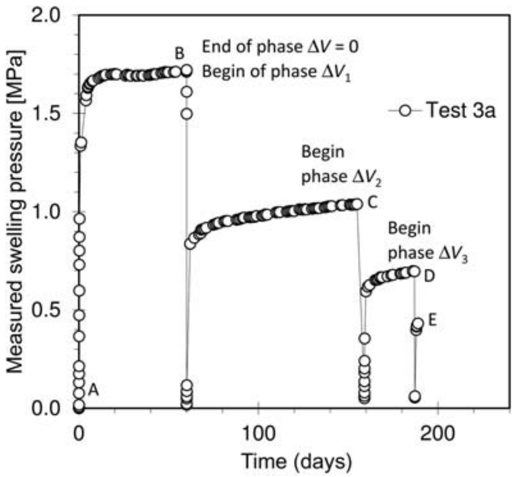

FIG. 6. Swelling pressure–time plot for the constant volume and relaxation test stages of specimen 3a.

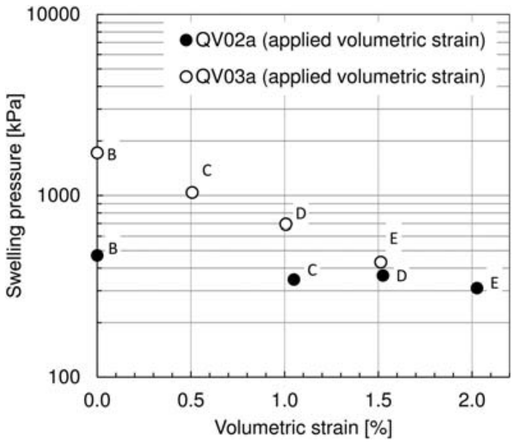

FIG. 7. Swelling pressure–volumetric strain plot for specimens 2a (filled symbols) and 3a (open symbols) (points B–E correspond to the respective points in Figs 5 and 6).

1.5%, respectively. Both samples showed a sudden decrease in swelling pressure due to the loss in contact immediately after the relaxation steps had been applied (Figs 5, 6), and with time, they gradually regained swelling pressure values which were smaller than the initial value. For sample 3a the decrease was more significant than for sample 2a due to the greater initial dry density and the higher swelling pressure at the end of the constant volume ($\Delta V = 0$). The swelling pressure

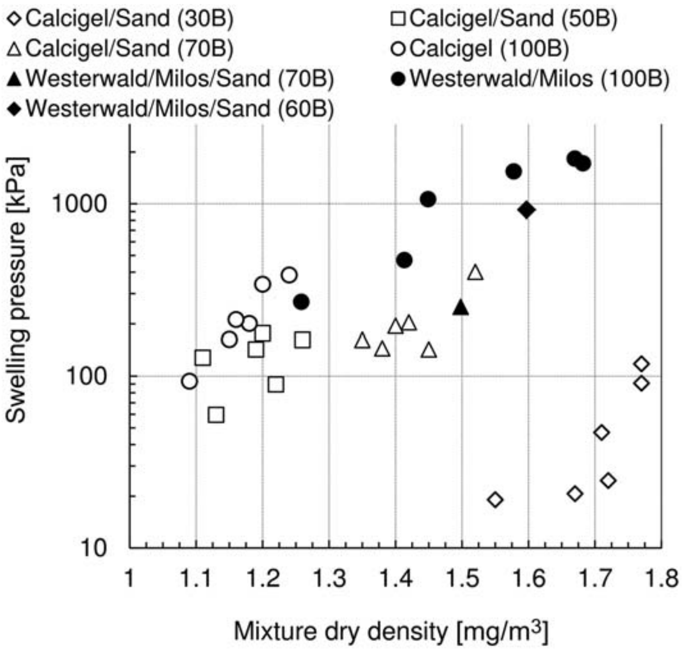

FIG. 8. Comparison of the measured swelling pressures of Westerwald/Milos bentonite (this study) and of Calcigel bentonite (Agus, 2005).

decreased for sample 2a from 470 kPa to 310 kPa and for sample 3a from 1720 kPa to 432 kPa.

Figure 7 shows the measured swelling pressure at the end of each test phase vs. applied volumetric strain. This relationship was necessary for the numerical simulation to prove the functionality of the dams. The kinematic description was thereby enlarged by swelling strains. Under the assumption of isotropic behaviour, the volumetric swelling strain was related to the hydrostatic stress using a logarithmic function as constitutive relation. The model parameters which occur were fitted to the experimental data. After implementing the model into the finite-element code, the system behaviour was analysed using different scenarios including the interaction of the bentonite swelling and host-rock, abutments and equipotential layers automatically. Thereby, functionality was proven.

Figure 8 compares swelling pressure *vs*. mixture dry density data of the Westerwald/Milos bentonite with data from the literature obtained for Calcigel bentonite. Both data sets comprise pure bentonite and bentonite/sand mixtures of different ratios. The bentonite/sand mixture with a ratio of 70:30 was used for the sealing. The dry density for the mixture was 1.49 g/cm³. The calculated dry density of the bentonite fraction according to Agus (2005) was 1.26 g/cm³. The specimen of the 100B Westerwald/Milos bentonite with a comparable dry density showed a similar swelling pressure. The measured swelling pressures of the Westerwald/Milos bentonite for the various mixture ratios were similar to those of Calcigel. Converting the *in situ* mixture densities achieved for the bimodal blend into a dry density of the bentonite fraction for the given mixture density and water content, the swelling pressure could be estimated using equation 1.

Development of the bimodal blend

As a first step, vacuum-extruded and sodium-activated bentonite pellets with a residual moisture content of ~16% were favoured. The pellets themselves showed a grain density (moist) of 2.0–2.1 g/cm³. The bulk density (moist) of a filled test column ranged between 1.1 and 1.2 g/cm³, however. It was assumed, therefore, that there is 30–40% pore space between the pellets. The main requirement of the development was to fill this space completely.

The first trials to fill the pore space with fine-grained bentonite granulates were rejected as being inadequate due to insufficient density. A blend of pellets and 0.2 mm bentonite granulates led to a bulk density of 1.3–1.4 g/cm³ in the laboratory. In addition, a first *in*

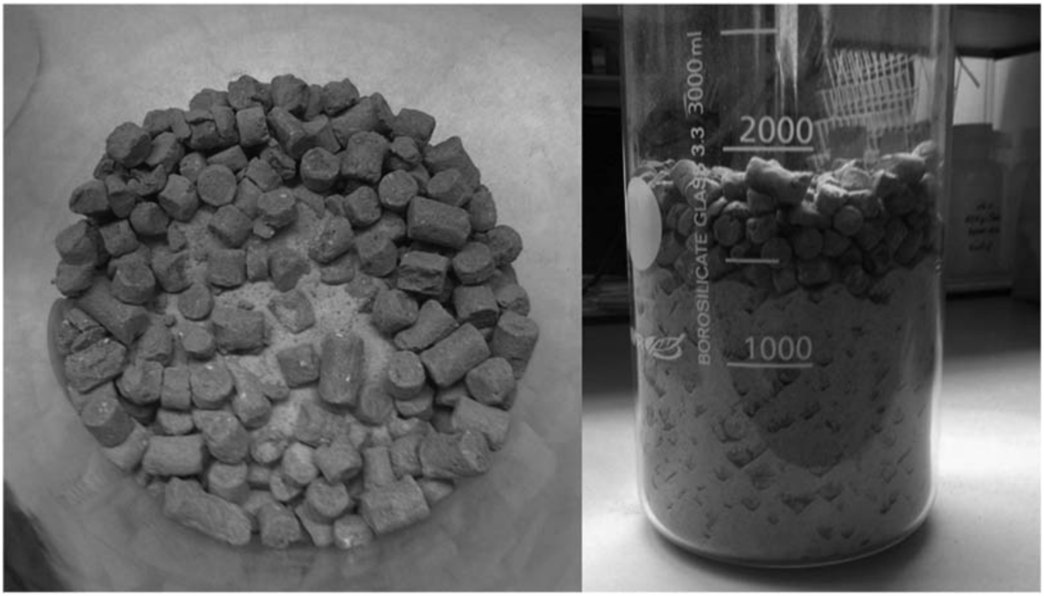

FIG. 9. Emplacement of the bimodal blend in a flask in the laboratory. The silica sand was added after the pellets, without vibration or compaction.

TABLE 3. Range of density and swelling pressure of the bentonite fraction in the bentonite/sand mixture calculated according to Agus (2005), determined in pneumatic tests.

Parameter	Minimum	Maximum
Bulk densities of bimodal blend (pneumatic tests) [g/cm³]	1.67	1.92
Corresponding dry density of bimodal blend [g/cm³]	1.45	1.67
Estimated swelling pressure of bentonite fraction in the mixture (calculated according Agus, 2005) [MPa]	0.28	0.90

TABLE 4. Realized bulk densities in the shaft and drift and expected dry densities and swelling pressures.

	Shaft	Gateway
Bulk density of bimodal blend [g/cm³]	1.72	1.74
Dry density of bimodal blend [g/cm³]	1.49	1.51
Estimated swelling pressure of bentonite fraction in the mixture (calculated according Agus, 2005) (MPa)	0.41	0.45

situ trial showed that a 300 m height fall did not generate adequate kinetic energy to achieve greater density after underground emplacement. Another reason for rejecting this material was the fast swelling of the fine-grained bentonite. Last but not least, the fine material that had to fill up the pore space should be an inert, non-swelling material with good settling or free-flowing properties. Finally, several trials in the laboratory revealed that quartz sand with nearly spherical shape showed the best performance to achieve an enhanced density. For the trials, the bentonite pellets were poured into a glass cup and silica sand was added subsequently until the residual sand was lying on top of the pellet filling (Fig. 9). Measurements in the laboratory showed a bulk density (moist) of ~1.7–1.8 g/cm³. The bimodal blend evaluated consisted of 70% bentonite-pellets and 30% quartz sand H35S.

In a second step, the laboratory-evaluated blend was tested in a scale-up experiment. Therefore, a silo truck was filled with 7 t of bentonite pellets. Subsequently 3 t of silica sand H35S were placed on the top of the pellets directly in the silo truck. The sand penetrated the voids between the bentonite pellets in the tank of the silo truck extensively.

The bimodal blend was moved pneumatically through a (horizontal) flexible pipe 80 mm in diameter and 100 m long, into an excavated earth pit. Buckets were placed in the pit and afterwards were dug out. The measured bulk density of the pneumatically blown bimodal blend determined in the buckets was 1.7–1.9 g/cm³. The swelling pressures expected, calculated

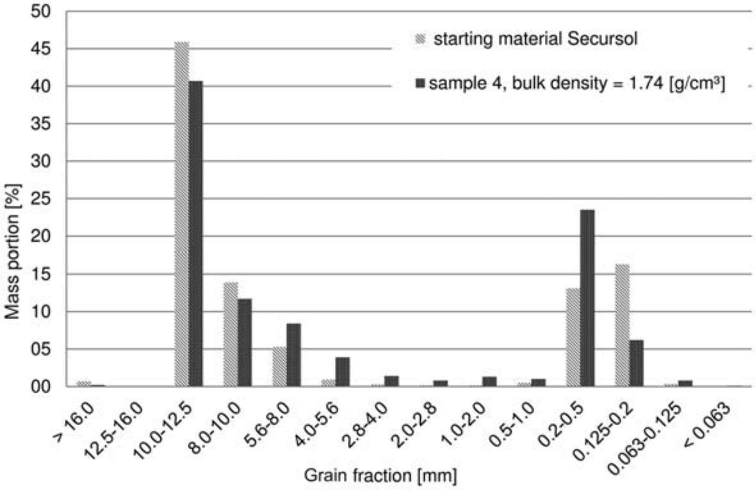

FIG. 10. Comparison histogram of the binary blend. The blend shows a bimodal distribution of the original material and after pumping the material through the pipe (sample 4).

according to Agus (2005) using equation 1, ranged between 0.28 MPa and 0.90 MPa (Table 3). The implementation of these values in a finite element code showed that these swelling pressures were sufficient for the functionality of the dams.

The final step in the development was an *in situ* test below ground. Therefore, a silo truck was filled with 10 t of the bimodal blend as described in step two. The blend was moved pneumatically by compressive air 300 m vertically below ground through a steel pipe (d = 100 mm) (DN100) and another 20 m horizontally through a flexible rubber pipe directly into the gallery. Once again, the density was measured by filling buckets underground. The bulk density was confirmed as in step two.

Due to the pneumatic transport down the shaft through a DN100 steel pipe and the abrasive properties of silica sand, the pellets were reduced in size and the proportion of the sand fraction was increased (Fig. 10). The silica sand also seemed to be slightly coarser after the emplacement underground due to the coating of the silica sand grains with a thin layer of bentonite after pneumatic transport. This effect is very positive with regard to the hydraulic conductivity of the bimodal bentonite-silica sand blend.

Following the results of the first trials in the laboratory, the scale-up trial in the field and a first trial below ground, it was very likely that the possible bulk density of the bimodal blend was ~1.75 g/cm³. Therefore, the hydraulic conductivity tests were carried out using samples prepared with this expected emplacement density.

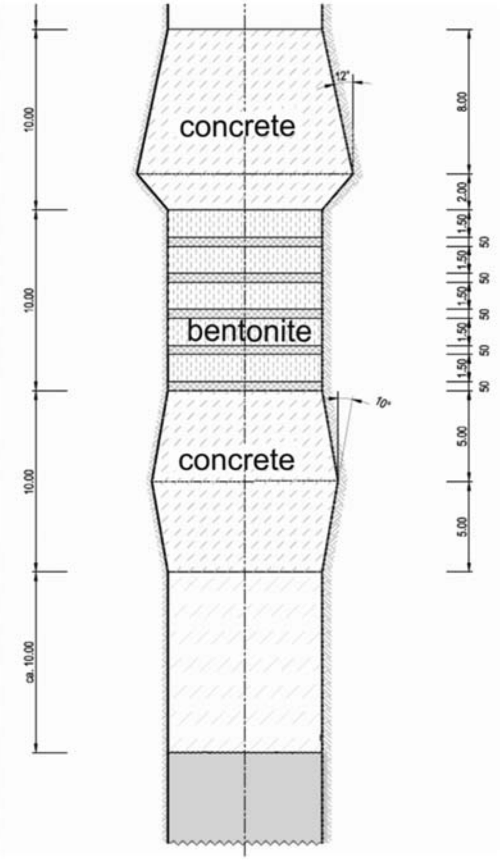

FIG. 11. Construction of the layered replacement for dam 59 in the Bockraden shaft with the abutments at the bottom and top and the SANDWICH in between.

PERFORMANCE OF THE SEALINGS

The dam in the shaft with a mean cross section of 8.8 m was constructed below the third floor (171 m below mean sea level). The conical abutments take the static load and the sealing consisted of five sand beds 0.5 m thick, each intercalated between five bentonite layers, each 1.5 m thick (Fig. 11). In the shaft a capillary rise of 0.5 m was adequate and a very fine-grained sand was used for the equipotential layers. Before installation of the sealing, the water flux of 25 L/min (with 7.5 L/min as rain) needed to be reduced to inhibit swelling of the bentonite during installation of the sealing. Therefore, gutters were installed at the top of the sealing and the accumulating waters of the rock that occurred in that height were pumped off. Above the working platform, a spray protection was installed to eliminate penetration of precipitation water. The shaft bricks had to be removed to obtain a flush connection of the sealing with the rock and to obtain the abutment cones.

The dry material was conveyed pneumatically through a pipe of 100 mm diameter. From the surface to the third floor, a steel pipe was installed. Flexible rubber hosepipes were used from the third floor to the working area. To avoid plugging in the pipe, which happened in the first trials, the lines must be laid so as to avoid kinks, sharp bends and stresses during the pumping operations. The volume of each sand and bimodal blend layer was measured to calculate the resulting tonnage of the building material. Marks on the shaft wall corresponding to the foreseen height of each layer enhanced the control of the emplaced quantity of sand and bimodal blend. After every second or third truckload, the filling of the layers was assessed on site. Thus, the material was emplaced, virtually

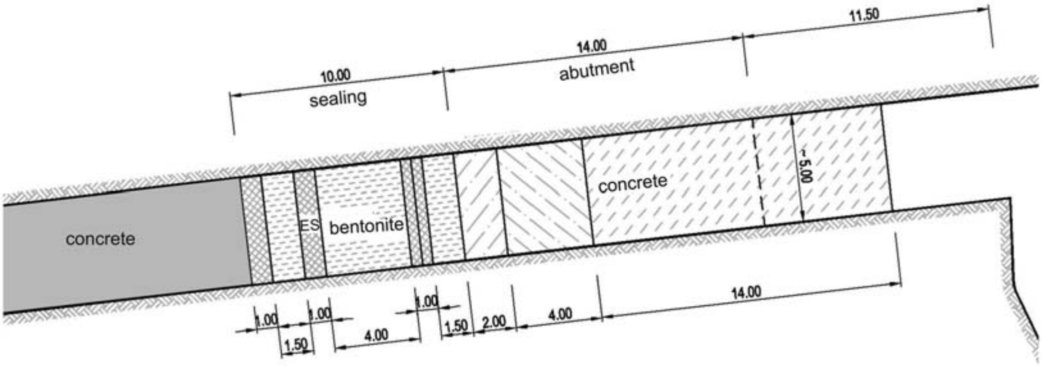

FIG. 12. Construction of the layered replacement for dam 71 in the gallery showing the abutments and the SANDWICH between them.

without interruption. However, after each emplacement of 3 m of material, the flexible rubber hosepipe was shortened and the working platform lifted up, which caused brief interruptions in the emplacement of ~1 h each. Shortening of the pipe was only possible after filling a sand layer in order to avoid a swelling of previously placed bentonite.

The density of the bentonite blend reached in the shaft was 1.72 g/cm³. With reference to the possible compression of the sand layers, the density was calculated to be at least 1.67 g/cm³, which corresponds to the lower limit of the required bentonite density.

The dam in the gateway was placed below the third floor of the Bockraden shaft (Fig. 12). In the gateway, three equipotential layers and bentonite sealing segments were installed. The three equipotential segments with the four-component mixture were 1 m thick each; for the sealing segment composed of the bimodal blend two sections of 1.5 m each and one main segment of 4 m thick were constructed for technical reasons. The mean height of the drift was ~4.2 m and the mean width was 5.3 m. Figure 13 shows in detail the contour of the drift with the SANDWICH installed. In the gateway, the material had to be transported horizontally over a distance of 35 to 45 m. The sections of the equipotential material and the bentonite material had to be installed vertically, which was implemented with the help of 'stay-in-place' formworks. First, the three equipotential segments of 1 m each were filled with the silty four-component mixture. In the gateway, a proctor density of 1.75 g/cm³ for the equipotential material had to be achieved. The dry material was moistened and consolidated manually in layers. The density obtained by this procedure was 97% of the proctor density for the three segments of the equipotential material. To avoid unfilled backfill areas the reinforcement steel mesh was partly trimmed.

Before inserting the bimodal bentonite sections, a short abutment dam was installed (Fig. 12). The 4 m-thick concrete dam could be crossed through a 700 mm tube gateway. The tube pipe for the bimodal bentonite crossed the dam at the top of the gateway.

Afterwards, the two smaller and the main bentonite sections were constructed, conveying the material in a dry way similar to the shaft. The bimodal blend could be moved pneumatically, directly to the top of the gallery (Fig. 13) without additional compaction. The density of the bimodal bentonite sections achieved was thus 1.74 g/cm³.

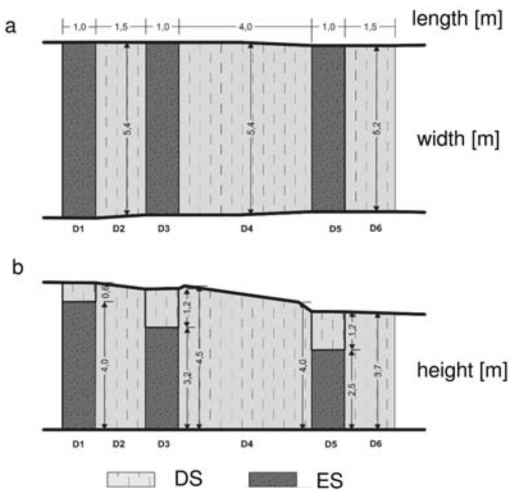

FIG. 13. Detailed section of the seal constructed in the drift: (a) horizontal projection; and (b) profile.

SUMMARY AND CONCLUSION

At the Ibbenbüren coalmine, the two high-pressure water-retaining dams are required to perform reliably under conditions of induced tension caused by further exploitation of the existing mining area. Therefore, a multilayer sealing system (SANDWICH) was installed and complete new sealing materials were developed, which were emplaced in a wet environment. As compaction on site was possible for neither the vertical nor the horizontal dams, the sealing material had to be designed as a self-compacting dry body. Due to water inflow from the host rock and mine, the emplacement had to be carried out without any interruption. Between the bentonite/sand sealing layers, sandy/silty equipotential layers were placed in order to achieve homogeneous saturation. A swelling pressure testing program was conducted to ensure an adequate potential for swelling-pressure development. For dry densities of 1.45–1.67 g/cm³ an evolving swelling pressure of 1.04–1.8 MPa for a 100% bentonite sample was measured under constant volume. Swelling potential still existed after a strain relaxation of up to 2%. The swelling pressure of a bentonite/sand mixture was also determined for verification.

In February 2014, the vertical dam was built within 3.5 days. During this time, ~800 metric tons of sealing bimodal bentonite blend and 180 metric tons of equipotential building material were emplaced. In May 2014, the dam in the gallery was emplaced within 1.5 days. Approximately 250 metric tons of bimodal bentonite blend and ~70 metric tons of equipotential building material were emplaced during that time.

The bulk density of the bimodal blend in the shaft was 1.72 g/cm³ and in the gateway 1.74 g/cm³. The swelling pressures for bentonite/sand mixtures were predicted based on swelling pressure–dry density relationship of the pure bentonite. For *in situ* conditions, swelling pressures of 0.41–0.45 MPa were expected. With a hydraulic conductivity of 4E–12 m/s, the water flow rate was predicted to be 54 L/y (litres per year) in the gateway and 26 L/y in the shaft.

All requirements for the emplacement of the building materials were fulfilled. Thus, the Bockraden project was the first successful underground construction built by self-compacting bentonite sealing materials in accordance with the KIT SANDWICH-system.

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