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Experimental pressure and sealing plug as part of the European DOPAS project – deep geological repository plug demonstration

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ABSTRACT: The objective of the DOPAS international project is to design a sealing-plug system for deep geological repository (DGR) use, to provide detailed plans for the design of such plugs, to test the characteristics of the materials to be used and the construction technology and to install four experimental *in situ* plugs. The Czech experimental pressure and sealing-plug (EPSP) experiment is being conducted in a rock environment consisting of granitoids at the Josef Regional Underground Research Centre. The concept of the experiment is based primarily on the use of materials and technology available in the Czech Republic and the principal aim is to demonstrate the technical viability and functioning of a pressure-resistant plug located in a future DGR. The completion of the EPSP experiment will contribute towards both the demonstration of how sealing-plug systems behave under real underground conditions and the long-term safety of a future DGR in the Czech Republic.

KEYWORDS: Deep Geological Repository, plugs, sealing system, bentonite pellets, low-pH concrete, laboratory physical models.

The programme for the development of a DGR for radioactive waste in the Czech Republic is based first and foremost on the safe disposal of long-lived, highly active radioactive waste. The safety of such repositories will be enhanced by the efficient performance of the plugs and sealing systems which will make up an important part of the overall disposal system. Several types of sealing plugs will be required, the function of which will be to provide for the sealing and closure of individual waste packages not only throughout the period of repository operation, but also following the permanent closure of the facility. Such plugs will have to provide a high level of resistance to the considerable pressure which will be exerted by hydrostatic forces and volumetric changes within the engineered barriers.

The objective of the DOPAS project is to design a sealing-plug system for DGR use, provide detailed plans for the design of such plugs, test both the characteristics of the materials to be used and the construction technology and to install four experimental *in situ* plugs.

This 4-year (2012–2016) project is funded by the European Commission financial resources (7th framework programme, EURATOM) and the project coordinator is Finland-based company, Posiva. A total of 14 partners from eight European countries are involved in the project (Posiva (Finland), ANDRA (France), DBE-TEC (Germany), GRS (Germany), NAGRA (Switzerland), NDA (UK), SÚRAO (Czech Republic), SKB (Sweden), ČVUT (Czech Republic), NRG (The

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Netherlands), GSL (UK), BTECH (Finland), VTT (Finland), ÚJV (Czech Republic)).

In 2012 the construction of a sealing plug commenced at the Äspö underground laboratory (Sweden) in a granitic-rock environment containing water with a relatively high level of salinity (~75 g/L) (Puigdomenech, 2001) compared to that of Czech granitoids (Pačes, 2010). In Finland a similar plug was subjected to testing at the Onkalo underground laboratory located on the island of Olkiluoto in a migmatitized gneiss-rock environment (Dixon *et al.*, 2013). In France, an experiment is underway at the Saint Disier laboratory focusing on research into sealing systems in claystones in which it is intended that the French DGR will be constructed (*e.g.* Montes *et al.*, 2004). The Czech EPSP experiment is being conducted in a rock environment consisting of granitoids at the Josef Regional Underground Research Centre (URC). The concept of the experiment is based primarily on the use of materials and technology available in the Czech Republic.

The objective of the EPSP experiment is to test both the materials and technology to be used for implementation rather than to test the specific design and performance of the reference disposal tunnel plug. At this early stage in the Czech geological disposal programme (SÚRAO, 2011), >50 y prior to the scheduled commencement of operation, it is considered by those involved more important to build knowledge and experience rather than to refine implementation designs for an, as yet, unidentified site with unknown mechanical, hydrogeological and chemical characteristics. Nevertheless, experience gathered by means of the testing of plug components at the Josef facility to date has provided a number of indications with regard to crystalline host-rock requirements which may provide support for the site-selection programme (White *et al.*, 2013).

The EPSP does not represent a specific plug or seal; rather it is being constructed at a similar scale to a disposal tunnel plug and will contribute specifically towards the development of a reference design for such structures.

LOCATION OF THE EPSP EXPERIMENT

The EPSP experiment is being conducted at the Josef URL which is located near the Slapy dam close to the villages of Čelina and Mokrsko in the Příbram district of Central Bohemia, Czech Republic.

The Josef gallery runs in a NNE direction across the Mokrsko hill rock massif. The total length of the main drift is 1835 m, with a cross-section of 14–16 m^2. The overlying rock thickness is 90–180 m. Two parallel tunnels lead from the entrance portals; each is 80 m long and has a cross-section of 40 m^2. The main gallery is connected to various exploration workings by a number of insets which follow ore formations and provide access to two further levels. The total length of the galleries is ~8 km; 90% of the breakings are not fitted with linings. The end of the main gallery is connected to the ground surface by means of an unsupported 144 m vent.

Geological diversity represents one of the great advantages of the Josef URL (Fig. 1). The rock environment consists of two basic geological formations each with a very different history and contact zones (Morávek, 1992). Moreover, each of the formations exhibits different physical and material properties which change in character towards the contact zone. These formations feature a variety of local fracture zones and intrusions which provide a high level of flexibility with regard to choice of the best location for conducting experiments depending on the conditions required, *e.g.*, fracture systems, rock stability, rock strength, mineralogy, *etc*.

The EPSP experiment itself is located within the M-SCH-Z/SP-59 experimental gallery niche. The niche was reshaped prior to the commencement of the experiment and the surrounding rock was improved by means of grouting so as to reduce water permeability (in order to allow for the higher pressure levels to which the plug would subsequently be subjected).

The technology required by the experiment is located in parallel niche M-SCH-Z/SP-55.

The two niches are connected by means of cased boreholes equipped with tubing for the circulation of the pressurization media (four leading into the filter and four into the pressurization chamber) and for monitoring purposes (five boreholes equipped with sealed cables).

The experimental rock niche is located in granodiorite and is traversed by quartz and quartz-carbonate veins with a maximum thickness of 14 cm. Information on dominant joint systems was originally recorded in historical mining documentation (see Fig. 2) which was subsequently updated according to map source documents owned by Geofond-Dobříš 1-9/34-24, M-SCH-Z/SP-59.

The detailed mineralogical study of the filling of the fissures was carried out in niche SP-59 in 2013; the sampling locations are shown in Fig. 2. Six samples were analysed by means of X-ray powder diffraction (XRD) at the Institute of Chemical Technology, Prague (X´Pert PRO with Bragg-Brentano geometry, Cu-$K\alpha$, 40 kV, 30 mA, *High Score Plus* software) and SEM at the Faculty of Science, Charles University in Prague.

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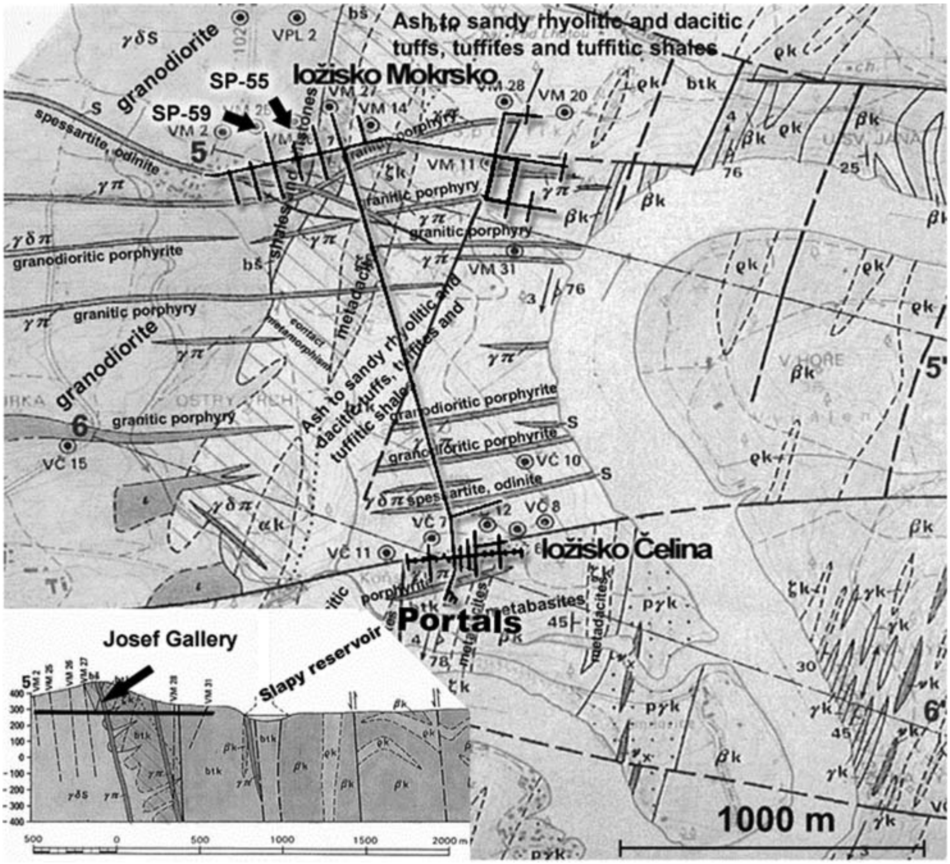

FIG. 1. Geology of the Josef Underground Facility (based on a map composed by the Czech Geological Survey, 1991).

The principal mineral phase filling the cracks and fissures within the experimental niche consists of quartz. Carbonates (mainly calcite) are also dominant. A number of accessory phases (≤0.5 wt.%) were also identified such as laumontite, gypsum and pyrite.

EPSP EXPERIMENT DESCRIPTION AND CONSTRUCTION

The EPSP experiment consists of the following principal components (see Fig. 3): a pressurization chamber, the inner glass fibre-reinforced shotcrete plug (1.8 m), the bentonite sealing material (2 m), a filter, an outer glass-fibre concrete plug (1.8 m) and the host-rock environment. The experiment also comprises a number of auxiliary structures such as permeable concrete walls, an extensive monitoring system and a service centre.

The experiment allows the use of a number of pressurizing media: air, water and a bentonite suspension. The pressurizing medium is transported to the pressurization chamber *via* 23 m-long connecting boreholes from the neighbouring service centre niche. The chamber itself is enclosed by means of a permeable concrete wall which served during the construction phase for supporting one of the main elements of the EPSP experiment – the inner glass fibre-reinforced concrete plug.

Rock preparation

Work on the EPSP experiment commenced with the reshaping of the rock niche. In order to keep damage to the rock mass to a minimum, the hydraulic wedge splitting method was used in combination with non-detonation (GBT) splitting; no explosives were used. This phase resulted in the adjustment of the niche profile and the excavation of the recesses required for the construction of the concrete plugs.

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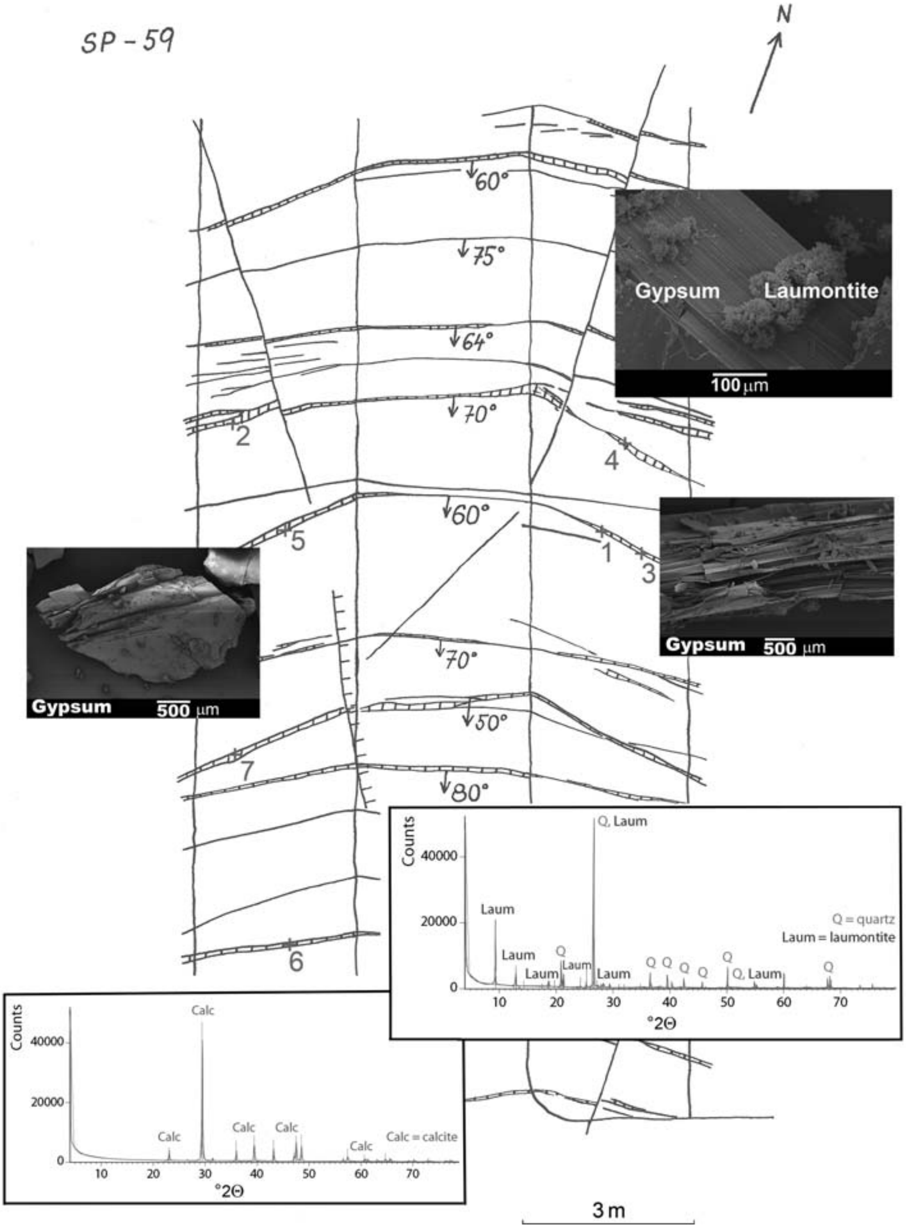

FIG. 2. SP-59 tectonics and mineralogy.

Once the reshaping work was completed, the rock-improvement phase commenced which involved the use of grout so as to improve the properties of the surrounding rock massif. Polyurethane-based resins were applied so as to reduce rock permeability in order to allow high-pressure loading of the experimental plug and to limit unnecessary leakage into the rock mass.

Pressurization chamber

The pressurization chamber (Fig. 3 section 1) serves as the primary location for the injection of the pressurization media. For this purpose the chamber was equipped with four pressurization tubes perforated at both ends and connected to the technology hub in a

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parallel niche *via* pipes leading through the connecting boreholes.

The rock surface of the pressurization chamber was highly uneven which led to its having an unnecessarily large volume; therefore, the volume of the chamber was reduced by means of the filling of redundant spaces employing shotcreting technology. This process also served as an important test for the subsequent installation of the technological equipment for the inner plug (using the same machine setup).

Once the shape had been adjusted, a waterproofing finish was applied to the surface of the chamber in order to mitigate potential leakage behind the chamber.

The final step consisted of the construction of a permeable separation wall between the chamber and the inner plug which served as the formwork for the shotcreting of the inner plug.

Inner plug

The inner plug (Fig. 3, section 3) makes up one of the key components of the experiment and verifying that it works efficiently represents one of the main objectives of the project. It has two basic functions: static and hydraulic which means primarily that it must ensure the mechanical stability of the entire system even under high-pressure conditions and, at the same time, must restrict flow through the plug so that the bentonite sealing is not damaged through the creation of erosion channels in the period in which the bentonite sealing zone is undergoing, but has not yet reached, full saturation.

The inner plug was emplaced over a continuous period of 23 h employing shotcrete technology. The concrete was produced at a mixing plant in Prague and subsequently transported by cement mixer trucks to the Josef URL (transportation time of 1–1½ h).

On arrival, the wet concrete mix was gradually reloaded onto smaller trucks for transportation from the entrance portals to the spraying machine positioned in the experimental niche (a distance of 2 km). Two small trucks were used on an alternating basis with a 40-minute turnaround period (*i.e.* a 20–30-min batch start interval).

The plug was constructed in layers commencing at the rear on the separation wall and gradually filling the plug space with shotcrete. The short breaks between the deliveries of the separate batches of wet mix were used for the installation of the instrumentation.

The contact zone between the plug and the rock mass was grouted using the same resin as that employed for the improvement of the rock mass itself. The quality of the sealing was checked *via* the pressurization of the chamber behind the plug by means of both water and air media.

Bentonite sealing section

A further major component of the EPSP consists of the bentonite sealant (Fig. 3, section 4), the purpose of which is to hydraulically separate and seal the experimental plug. Because of its exceptional swelling properties (and consequent self-healing capacity) and very low permeability, bentonite is particularly suitable for fulfilling this function. However, its sealing properties depend, in addition to its mineralogical composition, principally on its density. Therefore, in order to achieve the required density level, bentonite is used in the form of highly compacted pellets.

The pellets were emplaced between the inner plug and the filter. The lower parts (95%) of the bentonite sealing were emplaced and subsequently compacted (in-place compaction) using the vibration technique. The upper part (5%) was emplaced using shotclay technology (Pacovský & Šťástka, 2009; Šťástka *et al.*, 2014).

The total volume of the section is 23.7 m^3. It took a total of 8 days to emplace the bentonite into the sealing section of the experiment. The average dry density following emplacement was 1427 kg/m^3 with a water content of 18%.

The quality of sealing emplacement was tested by means of the sampling of both the material prior to emplacement and the finally emplaced material. Average density values for the section were calculated based on the mass balance of the emplaced material and the total volume of the section.

Filter

The filter (Fig. 3, section 5) was designed principally for the monitoring of seepage through the plug. Nevertheless, it is connected through the aforementioned boreholes to the service centre niche and can be used, if required, as an alternative pressurizing chamber. The design of the experiment even provides for alternative testing scenarios in which the filter can be used as the pressurizing chamber enabling the forced saturation of the bentonite sealant, the testing of reverse flow (firstly *via* the bentonite and subsequently *via* the inner concrete plug) and the testing of the outer concrete plug.

The filter consists of gravel held in place by two permeable separation walls (Fig. 3, section 2). The

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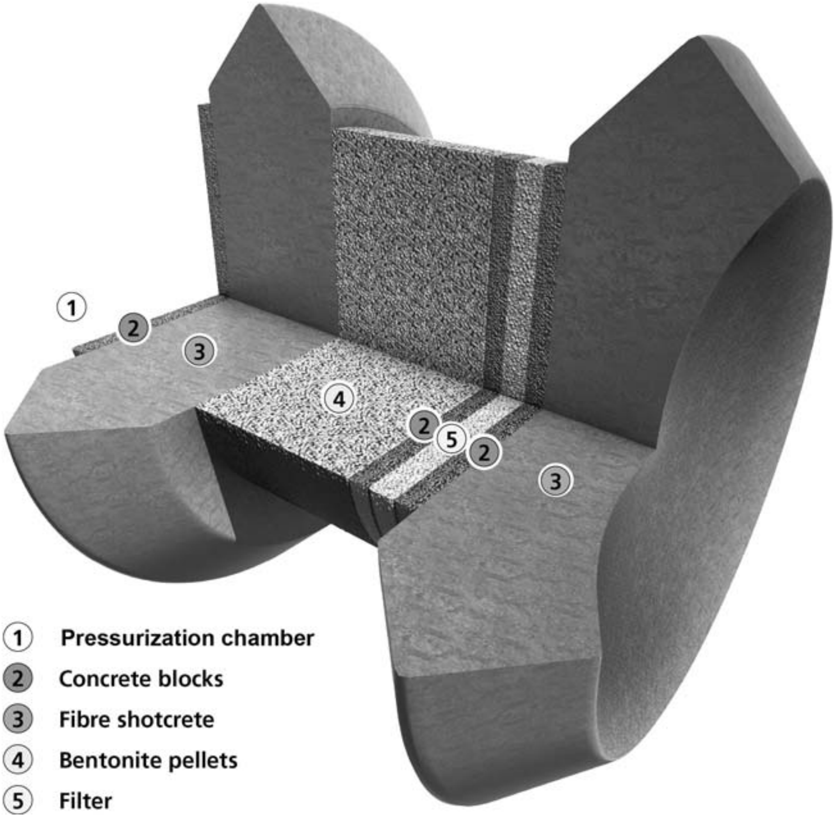

FIG. 3. EPSP scheme.

filter is equipped with a drain and the same set of injection tubing as the pressurization chamber.

The complete structure of the filter and the separation walls fulfilled a number of additional functions during the construction of the experiment. Firstly, they served to hold the bentonite in place during the emplacement phase with the filter being raised in stages as emplacement work progressed and, secondly, once the structure was completed they served as the 'lost' (hidden) formwork for the outer plug.

Outer plug

The EPSP is enclosed by an outer concrete plug the function of which is to mechanically stabilize the entire block (Fig. 3, section 3). The outer plug was constructed in the same way as the inner plug once the bentonite and the filter had been installed. The contact zone between the plug and the rock mass was grouted following the construction phase; the same resin was used as that employed for rock-improvement purposes.

MONITORING

One of the main objectives of the EPSP experiment is to verify the effectiveness of the sealing plug. It is essential, therefore, that the processes which occur within the plug be determined accurately. Hence, the experiment was fitted with a comprehensive instrumentation system which has been designed in such a way that it allows for the monitoring of the development of the principal variables at key stages of the experiment.

The key processes of, and locations inside the EPSP experiment have already been identified and sensors have been specially selected in order to capture the processes at work. The monitoring process focuses on water movement inside the experiment and the response of the experiment to pressurization (especially the deformation of the plugs):

(1) Water movement inside the experiment is monitored in terms of water in/out-flow, water-content distribution within the bentonite seal and

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water (pore) pressure distribution. The water content is measured using TDR 5TE sensors produced by DECAGON; the relative humidity is measured by means of EE071 sensors produced by E + E; the pore pressure is measured using VW 4500SHX-10 MPa piezometers produced by GeoKon.

(2) The mechanical response of the plug is monitored by means of strain gauges installed at key locations within the concrete plugs and instrumented rock bolts positioned within the rock mass. Moreover, contact-stress measurement is deployed between the rock and the plug. VW 4200A2 strain gauges produced by GeoKon are used in the plug and 4911-4X gauges in the rock mass. Contact stress is measured using VW 4810X-10 MPa heavy-duty pressure cells produced by GeoKon.

(3) Temperature distribution is also being monitored because it makes up an important indicator not only during the construction stage (hydration heat) but also during the loading of the experiment as a reference base for sensor compensation. Various temperature sensors are used – digital DS18B20, analogue LM35DZ and NTC resistors.

(4) The swelling pressure of the bentonite sealing is monitored by means of the use of pressure cells. VW 4810X-10 MPa heavy duty pressure cells produced by GeoKon are used.

In order to obtain high quality and reliable monitoring results from the various sensors, their positions within the EPSP as well as the quality of their emplacement are crucial; key locations have been identified and the placement of sensors has focused on those areas.

Several measures have been taken in order to ensure the provision of reliable data including cross validation (sensors working on different principles are used to measure similar phenomena) and redundancy. Only those sensors which have been pre-tested, calibrated and verified have been positioned within the experiment.

A further important aim of the experiment consists of the verification of the suitability of the construction technology selected for particular structures. The monitoring process therefore commenced prior to the start of the construction stage and will provide for the monitoring of the whole of the construction period which can be divided into the following phases according to main purpose: (1) the preparatory phase (calibration of the system and the collection of data for determining the static state of the rock massif); (2) construction work up to the completion of the inner plug (monitoring of the inner plug – the development of hydration heat/temperature, the monitoring of deformation and contact stress); (3) the testing of the inner plug (inner plug and rock environment response); (4) the completion of the construction of the experiment (inspection of the installation of the bentonite sealant and the outer concrete plug); (5) trial operation (checking of the functioning of the pressurization equipment and overall functioning); and (6) the main experimental programme (comprehensive monitoring of the behaviour of the whole experiment).

The monitoring system employs modern technology which allows for the immediate availability of the data collected to end users; the data are stored on a continuous basis in the specially designed measurement-system database. In addition to the measured data, which are stored in primary units by the system, the database also contains comprehensive information from individual sensors installed within the experiment as well as the log of the experiment. The web interface, which makes up an indispensable part of the measurement system, allows those involved to obtain a general overview of events occurring within the experiment. The basic information services provided by the interface include: a list of sensors which allows for the plotting of graphs over a selected period, the 3D visualization of the current situation, an overview of the overall functioning of the system and the log of the experiment. The data also form important input for the mathematical modelling of EPSP. The mathematical models are being refined continuously based on the data available. The initial (blind) models predicted the saturation of the bentonite over long time periods (years to decades) due to the various uncertainties involved (especially due to the unknown quality of the rock-fracture system following grouting).

MATERIALS

Bentonite

B75_2013 bentonite material was selected for the DOPAS EPSP seal. B75 bentonite consists of a Czech Ca-Mg industrially milled and sifted non-activated bentonite which originates from the Černý vrch deposit and is produced commercially by Keramost Ltd. The B75_2013 material was delivered in 2013 and, subsequently, the full range of laboratory tests was performed on the bentonite in order to verify its properties. In some cases the results of tests on B75_2010 bentonite were used for purposes of comparison (B75_2010 consisted of B75 bentonite which was delivered in 2010 and tested during the period 2010–2013, (Červinka *et al.*, 2012; Červinka & Hanuláková, 2013; Vašíček *et al.*, 2014).

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TABLE 1. Chemical analysis of bentonite B75; comparison of bentonites produced in 2010 (B75_2010) and 2013 (B75_2013) (Vašíček *et al.*, 2014).

Wt.%	B75_2010	B75_2013
SiO_2	51.91	49.83
Al_2O_3	15.52	15.35
TiO_2	2.28	2.82
Fe_2O_3	8.89	10.9
FeO	2.95	3.74
MnO	0.11	0.09
MgO	2.22	2.88
CaO	4.60	2.01
Na_2O	1.21	0.67
K_2O	1.27	1.05
P_2O_5	0.40	0.63
CO_2	5.15	3.66

TABLE 2. pH values of B75 leachates; comparison of bentonite produced in 2010 (B75_2010) and 2013 (B75_2013) at different solid/liquid (s/l) ratios; contact time: 28 days (Vašíček *et al.*, 2014).

s/l ratio	B75_2010	B75_2013
18.6 g/L	9.65	9.52
125 g/L	9.34	9.22

An industrial bentonite product named Bentonit 75 (B75 – Černý vrch deposit) was slightly different from bentonite studied previously, originating from the Rokle deposit (raw samples as well as factory-produced B75). Table 1 provides a comparison of the results of the chemical analysis of B75_2010 produced in 2010 which was used in previous projects and bentonite B75_2013 produced in 2013 and used in the EPSP project described here. Testing of the pellet-production process was performed using this material. The differences in the properties (free swelling, ionic form, pH of the suspension) of the two materials is probably the result of the processing technology and/or the differing source of the raw bentonite (different deposit or a different part of the same deposit). A comparison of the leachate pH of the two materials in distilled water is provided in Table 2 in which the results of the suspension pH for different solid/liquid ratios after 28 days are shown. The analysis of B75 leachates in distilled water was performed for bentonite samples from both 2010 and 2013 at different solid/liquid ratios. The concentration of Na^+ in B75_2013 leachates is significantly less than in those of B75_2010 (Table 3).

The main factor affecting the properties of B75 produced in recent years is the processing technology. The partial activation and/or contamination caused by the presence of an activation reagent affected the composition of the water suspension or water leachate, the cation exchange capacity and the bentonite pore-water composition. The chemical composition of the B75_2013 sample (the material employed for the verification of the selected parameters) was different

TABLE 3. Chemical analysis of B75 leachates – concentrations of major cations; comparison of bentonite produced in 2010 (B75_2010) and 2013 (B75_2013) at different solid/liquid (s/l) ratios (Vašíček *et al.*, 2014).

s/l ratio c (mg/L)	18.6 g/L	27.9 g/L	37.2 g/L	62.5 g/L	100 g/L	125 g/L
B75_2010						
Na^+	93	96	132	190	255	260
K^+	5.6	7.0	7.9	10.8	11.6	11.6
Mg^{2+}	0.54	0.88	1.10	1.70	2.20	2.90
Ca^{2+}	1.91	1.94	2.07	2.19	2.06	2.77
B75_2013						
Na^+	57.9	80.1	85	81.7	123.7	123.5
K^+	8.7	9.3	9.1	8.0	12.4	12.6
Mg^{2+}	3.7	2.5	2.4	3.3	4.1	3.6
Ca^{2+}	1.8	2.1	2.5	2.9	3.4	2.7

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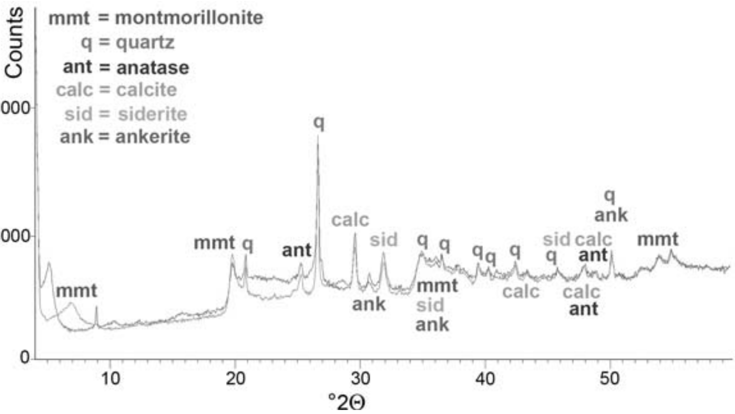

FIG. 4. XRD patterns of a B75_2013 bentonite bulk sample.

from the samples studied previously, especially in terms of the amount of total Na, Ca, Fe and carbon/carbonates (Vašíček *et al.*, 2014).

The XRD traces of B75_2013 bentonite are shown in Fig. 4. The amount of montmorillonite (Ca/Mg type) varies from 59 to 67 wt.% (calculated using the *CQPA* recalculation program (Klika & Weiss, 1993) based on XRD data and chemical analysis). Quartz and carbonates (calcite, siderite and ankerite) are subordinate. Anatase is an accessory phase, the amount of which is ≤2 wt.%.

From the geotechnical point of view, bentonite was characterized by the liquid limit, swelling pressure and hydraulic conductivity; the liquid limit is ~170% and the swelling pressure and permeability depend on the dry density of the material (ρ_d). Swelling pressure potentially increases from 1 to 8 MPa for a material with $\rho_d = 1.26–1.64$ g/cm^3. For an average $\rho_d = 1.4$ g/cm^3, *i.e.* the dry density value of the bentonite in the experiment, swelling pressure was ~2 MPa. Hydraulic conductivity for the same range of $\rho_d = 1.26–1.64$ g/cm^3 decreased gradually from 10^{-12} m/s to 10^{-13} m/s (Vašíček *et al.*, 2014).

The B 75 bentonite was used in the form of pellets (Figs 5 and 6) with a dry density value of 1900 kg/m^3 and with a target average dry density following emplacement of a minimum of 1400 kg/m^3.

Two types of pellets were used: types A (Fig. 5) and B (Fig. 6). Type A pellets were produced using the die roller extrusion process and have a cylindrical shape with a diameter of 12 mm and are up to 40 mm long. These pellets were used for the 95% (see above) of the sealing section; they were compacted following emplacement using a vibration desk.

Type B pellets were produced using a roller press and have an irregular plate-like shape with sides of up

FIG. 5. Type A pellets.

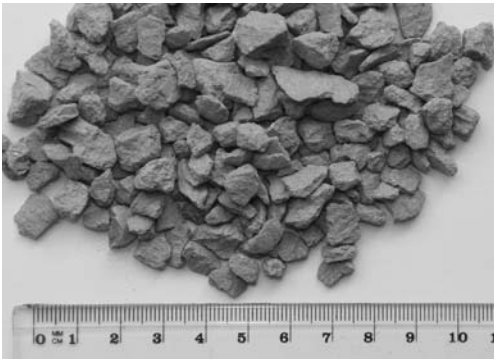

FIG. 6. Type B pellets.

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to 50 mm and a thickness of up to 10 mm; a fraction of 0.8–5 mm was used in the EPSP experiment. These pellets were applied using shotclay technology (Pacovský & Šťástka, 2009; Šťástka *et al.*, 2014).

Concrete

Concrete/cement materials are being used in the construction of EPSP in the form of concrete brick walls and the inner and outer shotcrete plugs. The concrete bricks used for the construction of the separation walls consist of commercially produced bricks made from common concrete and no limitations were prescribed nor material characteristics suggested for the use of this material. The concrete walls were built so as to facilitate the construction of particular parts of the EPSP experiment. The walls provide both a formwork for concrete spraying and separation between the bentonite part of the plug and the filter.

The inner concrete plug represents one of a number of sealing components in the EPSP experiment and is made up of sprayed fibre concrete. The main role of the concrete plugs is to fix the internal bentonite plug section in place and to ensure that its dimensions remain the same following the swelling of the bentonite. However, should the direction of pressurization be reversed, the outer concrete plug will have to perform as well as the inner concrete plug and, therefore, the requirements of the outer concrete plug are the same as those of the inner concrete plug. The outer concrete plug is also designed to hold in place all the various components which make up the EPSP experiment. It was suggested that the concrete material of the inner and outer plug sections would not influence the bentonite part of the plug (as opposed to the highly alkaline leachates of common concretes) due to the reduced pH of the leachate. The addition of glass fibres was suggested to enhance the physical properties of the concrete, *i.e.* in terms of limiting the formation of cracks and shrinkage and enhancing strength parameters without having to use pre-placed reinforcing materials. The concrete used in the construction of the inner and outer concrete plugs was applied by means of shotcreting technology.

The material properties of the concrete plugs were set so as to fulfil the following limits (accompanied by testing norms and procedures) (see Table 4).

Low-pH concrete mixtures were developed, on an experimental basis, in cooperation with ÚJV Řež (in the Czech Republic) and the subcontractor (Metrostav). The final two mixtures developed were tested for suitability for application using shotcreting technology in an experimental niche at the Josef URL. The final concrete mixture fulfils all the technical and technological requirements set and also has the advantage that it can be applied physically in the constrained conditions of the underground experimental niche using spraying technology by the personnel of all the cooperating institutions and regardless of the engineering techniques employed. The composition of the concrete used is as follows: cement CEM II/B-M, micro silica, aggregates 0–4 and 4–8, glass fibres, a plasticizer, retardant and accelerator. The exact 'recipe' of the mixture is a corporate secret of the subcontracting company (Metrostav) which constructed the EPSP concrete plugs.

One of the most important qualities of the concrete materials used in the construction of the plug consists of the pH value of the extract/leachate. The project requires that the concrete mixture should be 'low-pH concrete', which generally means extract-pH values of 11.7 or less. The recommended procedure for the pH determination of low-pH leachates from concretes is described in the SKB R-12-02 report: 'Development of an accurate pH measurement methodology for the pore fluids of low-pH cementitious materials' (Alonso *et al.*, 2012). A reduction in the pH of the leachate of cement mixtures can be obtained by the partial replacement of the cement by an alternative type of binder; it can also be modified by increasing the ratio of fine SiO_2 (microsilica/silica fume) to the cement content.

Several samples were taken during the construction of the inner and outer concrete parts of the EPSP experiment to test the leachate pH; all the samples were found to fulfil the limits set for pH, *i.e.* the values ranged from 11.4 to 11.5.

Tests on specimens prepared during the construction of the concrete plugs for the purpose of standard civil engineering tests proved that they fulfil the limits for the declared properties of the shotcrete. The results of laboratory testing performed at an accredited testing laboratory were: compression strength: 44.4 MPa and flexural strength: 5.8 MPa (Svoboda *et al.*, 2015).

LABORATORY PHYSICAL MODELS

The EPSP underground laboratory experiment will not be dismantled during the course of the project. Moreover, the laboratory work plan also proposed the construction of physical models of plugs at the laboratory scale the aim of which is to gather data for the subsequent calibration of numerical models of the saturation of the bentonite material and to study interaction processes principally on the concrete–

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TABLE 4. Requirements and limits for concrete-plug material.

	Value/limit	Procedure reference
Leachate pH	<11.7	Alonso *et al.* (2012)
Compressibility strength	>30 MPa	ČSN EN 12390-3
Flexural strength	>3 MPa	ČSN EN 14488-3
Hydraulic conductivity	$<10^{-10}$ m/s	ČSN CEN ISO/TS 17892-11
Fibre content	>3 kg/m^3	EN 14488-7

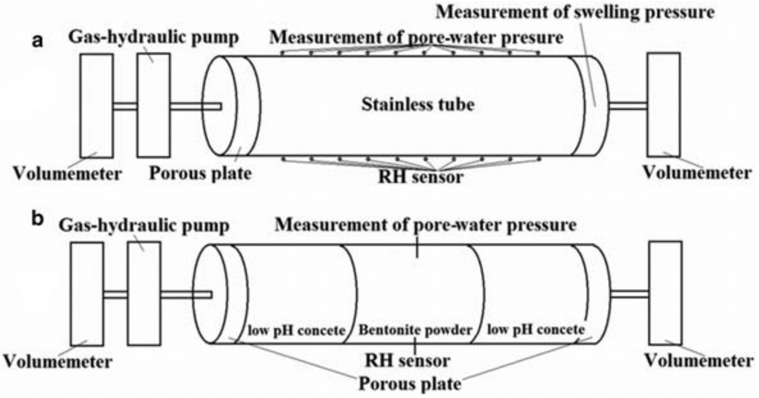

FIG. 7. Schemes of the laboratory physical models: (A) PHM – physical hydraulic model; (B) PIM – physical interaction model.

bentonite interfaces. Hence, two types of laboratory physical model were constructed: physical hydraulic models (PHM) intended for the study of bentonite saturation, and physical interaction models (PIM) constructed for the study of concrete–bentonite interaction.

The PHM models consist of stainless steel chambers with a cylindrical shape and approximate dimensions of 0.45 m in length and 0.1 m in diameter; the models are equipped with sensors for the recording of the distribution of water content/relative humidity within the bentonite material (Fig. 7a). Bentonite with an estimated bulk density of 1.4 g/cm^3, the same bulk density as is assumed in the EPSP experiment, was pressed into the test chamber and saturated gradually with synthetic granitic water (SGW) under pressure of up to 2 MPa. Laboratory-prepared synthetic granitic water, SGW (Havlová *et al.*, 2010), based on the statistical evaluation of Czech granitic-massif groundwater (depths of between 20 and 200 m), was used in the laboratory tests so as to simulate, as far as possible, the conditions to which the *in situ* experiment is subjected. The B75_2013 Czech bentonite is used in both the EPSP and laboratory models. The compositions of the bentonite and the water are shown in Tables 1 and 5. The PHM model will be dismantled following the conclusion of the experiment and divided into layers with an estimated thickness of 1 cm. The water

TABLE 5. Composition of the synthetic granitic water (SGW) (Havlová *et al.*, 2010).

SGW composition (mg/L)									
Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-	F^-	pH
10.6	1.8	27.0	6.4	42.4	27.7	6.3	30.4	0.2	8.3

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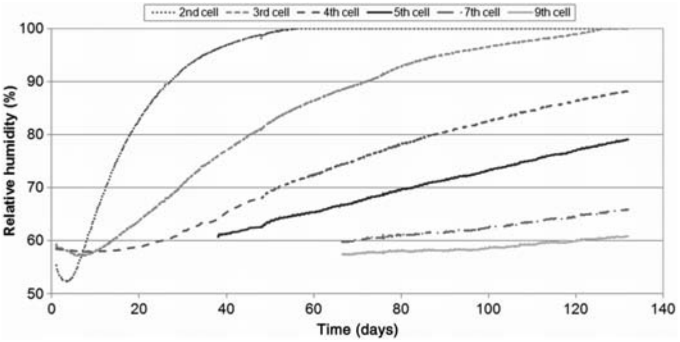

FIG. 8. PHM – evolution of relative humidity in the bentonite B75_2013 pellets (final dry bulk density 1.4 g/cm^3) during SGW saturation at 2 MPa after 4 months of experimentation.

content in each layer will then be determined so as to compare the data obtained *via* continuous measurement and that obtained following the dismantling of the model.

The physical models constructed for the study of the interaction of materials used in the experimental plug were designed as shown in Fig. 7b. Exactly the same materials as those used in the experimental EPSP plug are being used in the laboratory models, *i.e*. concrete and bentonite. The PHM model was gradually saturated by means of SGW up to a pressure of 2 MPa. The inflow and outflow of water are being monitored continuously, accompanied by the analysis of the physical-chemical properties and chemical composition thereof.

Both the PHM and PIM laboratory-model experiments are ongoing in accordance with the project schedule. Only interim results are available at the present time, therefore; for illustration purposes, saturation profiles from the PHM model, which is filled with compressed bentonite pellets, are shown in Fig. 8. Outflowing water from the PIM model is being sampled and analysed on a continuous basis. Results to date demonstrate that SGW water which has interacted with the bentonite and concrete in the PIM model is enriched principally with Na, K and Ca ions, carbonates and sulfates. The origin of the materials bearing these components and the leached and interacted amounts thereof will be evaluated following the conclusion of the experiments. In addition, the physical-chemical changes within the materials and mineralogical analysis will be studied following the dismantling of the models.

Both the hydraulic and interaction laboratory models will be dismantled after ~1 year of experimentation. The saturation of the bentonite material and water distribution will be determined as will the mutual interaction of the bentonite and the low-pH concrete. Data obtained during the experimental phase and following the dismantling of the laboratory physical models will be used for the subsequent verification and calibration of the numerical models of both the laboratory physical models and the experimental EPSP plug.

CONCLUSIONS

As the result of the successful construction of the EPSP, the first objective (the demonstration of the suitability of the technology) of the DOPAS EPSP experiment has been achieved. A number of 'alternative' technologies (such as shotcreting, shotclay application and GBT) and materials (low-pH shotcrete, bentonite pellets) have been tested successfully and the experiment is ready for the commencement of the experimental phase.

The behaviour of the plug will continue to be monitored comprehensively throughout the duration of the experiment. The final assessment of the experiment will involve the use of numerical analysis and modelling techniques. Finally, it is envisaged that the successful completion of the EPSP experiment will contribute towards demonstrating how sealing-plug systems behave under real conditions and, thus, will help to answer one of the many outstanding questions concerning the long-term safety of a future deep geological radioactive-waste repository in the Czech Republic.

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