Development of a Backfill Material for LILW and HLW Disposal Galleries in the Current Belgian Geological Disposal Concept – 15374

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ABSTRACT

In Belgium, it is planned to dispose of long-lived and high-level waste in an underground facility. After disposal of the waste, the galleries will be backfilled to provide stability to the galleries and to limit the amount of voids in the repository. To achieve those goals, the backfill material has to have a good flowability, a negligible bleeding, and a limited shrinkage. A limited grain size is also required to allow the injection of the backfill material. Despite the fact that the backfill supports the gallery lining, its strength must be low enough to enable the retrieval of the waste packages. The backfill material has to be chemically compatible with the Boom Clay and the waste packages. This means that it should not unduly perturb the clay or disposal packages. The thermal conductivity of the backfill material in the galleries containing high-level and thus heat-generating waste must be high enough to allow sufficient dissipation of the decay heat into the surrounding clay.

Based on these objectives, material requirements were specified and the development of a backfill mixture was carried out. Initially, the mix composition was optimized in the laboratory. Thereafter, the backfill process of a gallery section was simulated. The investigations illustrate that this mixture can be transported via pipelines through the shaft and drifts and would fill completely the backfill sections in the galleries. Measurements of the porosity, the pore solution composition, the thermal material properties, and the strength illustrate the compliances with the requirements and the feasibility of backfilling the disposal galleries.

INTRODUCTION

The Belgian National Agency for Radioactive Waste and enriched Fissile Material ONDRAF/NIRAS is studying the disposal of low and medium activity level, long-lived waste (category B) and high activity, heat-generating waste (category C) in an underground facility. The repository is built at a reference depth of approximately 230 m in the Boom Clay host rock. Two shafts are built for personnel and material transfer and to provide ventilation during the construction and operation of the repository. A third shaft will be constructed for the waste transport. The shafts are connected via horizontal access galleries. The disposal galleries are constructed perpendicular to the access galleries. They are blind or dead-end galleries with a diameter of approx. 3.0 m and a length of 1,000 m. Fig. 1 shows an overview of the repository layout.

The galleries in the clay will be lined with concrete wedge blocks. In the order to transport and to support the waste packages after disposal, the galleries are outfitted with a concrete floor. It is planned to backfill the galleries section by section with a cement-based material, because grout injection is assumed to offer better opportunities for achieving the industrial performance that is required to backfill such volumes in a relatively short period of time. The current planning assumes a volume of the sections of approximately 85 m³, which will be backfilled in three and a half hours. Seals will be placed at the front-end of the disposal galleries.

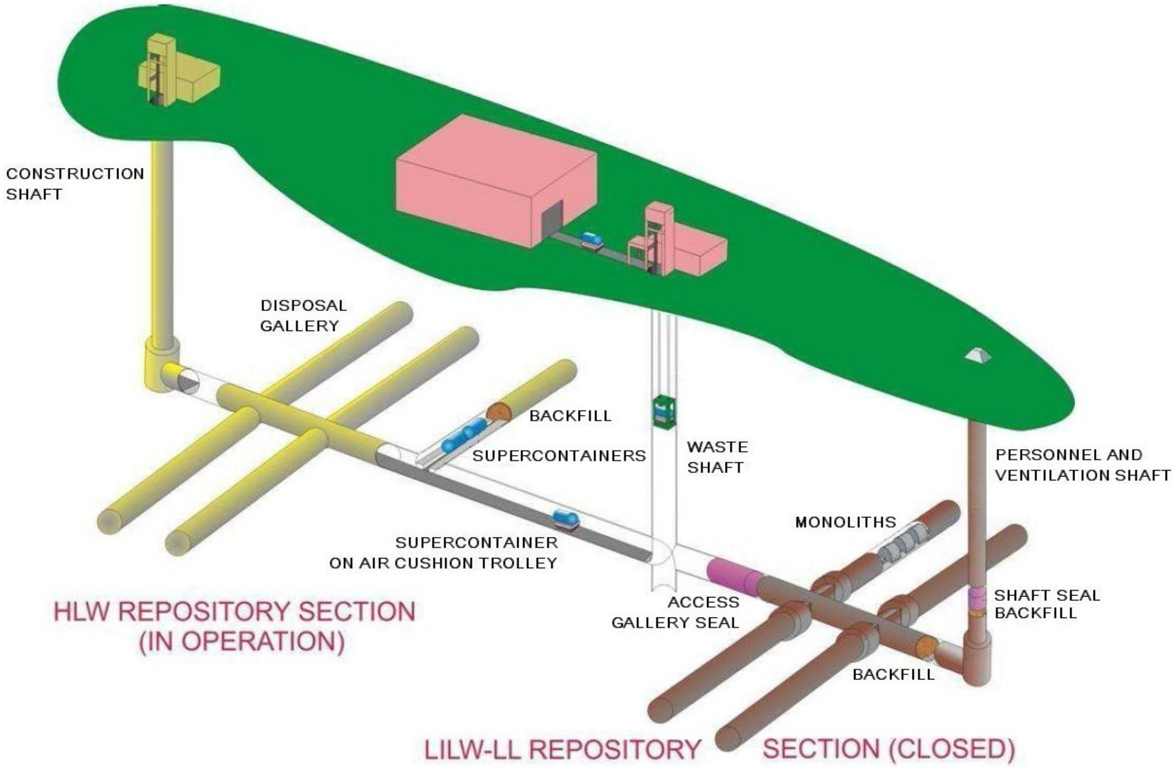

Fig. 1. Repository design consisting of a category B waste section and a category C waste section [1].

The main functions of the backfill mortar are (1) isolating the waste by forming an extra barrier to the waste, (2) providing the galleries with stability and thus avoiding a gallery collapse and (3) reducing the voids in the repository which is a regulatory requirement.

As the backfill needs to realize a high filling degree, it has to show good flowability, negligible bleeding, and limited shrinkage. The grain size is limited to allow the injection of the backfill material. Another important requirement for the backfill follows from the potential requirement for waste retrievability. This means that the strength of the backfill has to be sufficient low so that the backfill can be removed at a later stage. In addition, a high porous backfill might be envisaged as it can provide a storage volume for gas generated in the repository and consequently limit the gas pressure build-up. This is in particular important for the category B waste for which the gas generation is expected to be more significant than for the category C waste.

The backfill material has to be chemically compatible with the Boom Clay host formation and any other component of the disposal system like the gallery lining and the waste disposal packages. This means that it should not unduly perturb the clay or disposal packages. Finally, the thermal conductivity of the backfill material in the category C waste disposal galleries must be high enough to allow sufficient dissipation of the heat from the category C waste into the surrounding clay.

Furthermore, it has to be thermally stable under the maximum temperature that will occur in the backfill material.

DEVELOPMENT OF THE BACKFILL COMPOSITION

Pumping is an efficient and reliable means to transport backfill into underground excavations. In addition, this method reduces material transports via the shaft hoisting system. Consequently, it is planned to produce the backfill material above ground and to pump it into the galleries. Taking into account this well-proven technique and the objectives of the backfill operation, material requirements for the ingredients and the backfill composition were developed and specified. In order to ensure the long-term conformity with the first order specifications, the chemical and physical effects from the environment have to be considered. Traditional construction and civil engineering takes this aspect into account by the defining so-called exposition classes. This concept can be adapted to a backfill material in mines and results in the specification of additional material requirements. Before starting the experimental work, this catalog of requirements was compiled and described, and the respective storage and preparation conditions of the test samples were defined.

Due to diversity of requirements, it was to be expected that the backfill will be a multi-component material, which consists cement, filler, aggregate, water, and – where appropriate – an admixture to optimize the material behavior. For the selection of the ingredients, the chemical requirements are most important. It is well-known that soluble chlorides and sulphur-containing substances can induce or enhance corrosion of (stainless) steel. As a consequence, limitations were specified in accordance with European concrete standards to avoid corrosion of the steel envelope of the supercontainers. Moreover, it is not allowed to use slags or slag-containing materials due to their high sulfide content [2]. This decision restricts the selection of cements and fillers as blast furnace-slag cements, so-called CEM III-cements according to EN 197-1 [3] and slag-containing supplementary cementitious materials which are frequently used materials in Europe.

Due to the potential to increase the mobility of radionuclides, the content of organic materials has to be kept as low as reasonably achievable. In addition, the content of total organic carbon of each ingredient must not exceed 0.20 % (cf. EN 197-1, [3]). Coal fly ashes and slates were not considered during the further material selection. In addition, the use of organic admixtures has been severely restricted. It is possible to add superplasticizers with polycarboxylate ethers and air-entraining agents.

In an alkali-silica reaction (ASR) alkali-sensitive SiO_2 constituents react with the alkali and hydroxide ions to form an alkali silica gel and the consumption of hydroxide ions lowers the pH-value of the pore solution. To avoid this effect, only the use of chemically inert, quarzitic river sand as aggregate was allowed. To minimize the addition of dissolved harmful components, only potable water can be used for the mixing of the backfill material.

These precautionary measures ensure that the backfill provides a chemical environment consistent with the design concept and does not disturb the alkaline corrosion-protective environment. In accordance with the restrictions and the general experience and knowledge regarding the influence of the ingredients on the material behavior, a Portland-limestone cement (CEM II/A-LL), limestone (calcareous powder), barite, iron oxide powder, silica fume (filler), and sand (aggregate) were selected as potential ingredients of the backfill. Initially, the material properties of three basic mixtures were investigated in the laboratory and compared with the requirements.

Laboratory Investigations

When a mix is pumped, water transmits the pump pressure to the slug. But if the free space between the aggregates is not filled with fine grained particles, or the content of these particles is too low, variations of the pump pressure can cause segregation forcing the water through the mix. When this happens, the lubricating layer is lost, the coarse particles interlock, friction between the particles and the pipeline increases and the mix stops moving in the pipeline. A negligible bleeding, which is the development of a water layer on the surface of a suspension and segregation resistance, defined as the capacity of a suspension to preserve a homogeneous grain size distribution, are therefore essential requirements for a trouble-free operation of the pump unit [4]. These properties must be guaranteed to ensure a high filling degree of the galleries and the development of a homogeneous backfill. Moreover, the pressure during the pumping process and the spreading behavior in the galleries depend on the consistency of the backfill material. Measurements of the flow behavior and its dependence on time were therefore an essential part of the investigations. Currently, it is assumed that a good flowability must be achieved over a period of time of approximately 5 hours to ensure a high backfilling degree.

During the first test series increasing amounts of filler were added to mixtures with identical quantities of cement, aggregate, and water. Three types of river sand were used as aggregate to improve the dispersion of the fillers [5]. The tests illustrate that the quantity of the filler, necessary to achieve a non-bleeding and segregation resistant suspension, increases in the order silica fume (SF, Sika Silicoll P), barite powder, and limestone powder. The trend is influenced by the grain size of the fillers. SF (microsilica) consists of spherical particles with an average particle size of 150 nm. The specific surface are is between 18 m²/g and 30 m²/g.

In contrast, mini-slump tests on a dry glass plates showed a decrease in the flowability. As a result of increasing amounts of filler and solids a decrease in gas permeability, porosity and an increase in the strength can be expected in the given order of the fillers. According to this simple variant study, the decision was easy to focus the following studies on mixtures with SF. Fig. 2 shows an example of a mixture with SF.

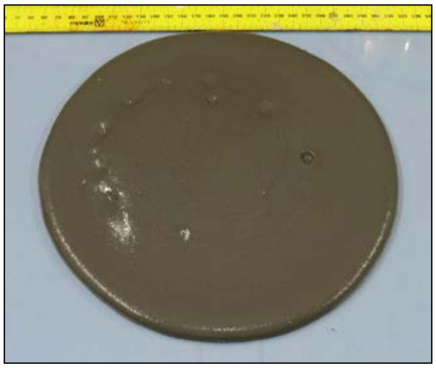

Fig. 2. “Mini-slump cake” of a mixtures containing 11.83 wt.-% cement, 14.20 wt.-% SF, 23.67 wt.-% sand, 50.30 wt.-% water (mini-slump 235 mm). The water-cement-ratio is 4.25.

The first test program illustrates the significant influence of the silica fume and water content on the bleeding and the segregation resistance of the mixtures. This is not surprising as silica fume has an extremely low particle size and increases the yield strength of suspensions. Fig. 3 shows the silica fume and water content of mixtures at the borderline between bleeding and non-bleeding mixtures. The corresponding border line of the segregation behavior lies in the field of non-bleeding mixtures. Accordingly a segregation of sand can be excluded for non-bleeding suspensions. In this case, the materials contain enough fine-grained particles (cement, SF), which avoids the segregation of sand.

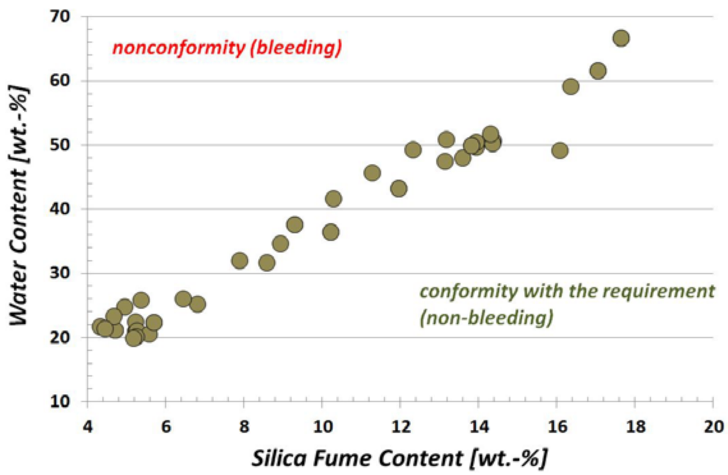

Fig. 3. Results of laboratory bleed water tests which were carried out to identify the border between bleeding and non-bleeding mixtures. Non-bleeding mixtures show no segregation of sand particles.

The mini-slump was measured after mixing times from 30 minutes to 5 hours. No significant changes of the mini-slump were observed over time, and it is possible to describe the influence of the mixture composition on the test results. The influence of the water and the sand content of the mixtures is particularly conspicuous (Fig. 4, Fig. 5). It is assumed that mixtures with a mini-slump of more than 200 mm have a sufficient flowability. According to correlations it was calculated that the backfill shall have cement, silica fume, sand, and water contents of > 11.4 wt.-%, > 11.9 wt.-%, < 33.5 wt.-%, and > 43.5 wt.-%, respectively. This approach results in a minimum water-cement-ratio of 3.8.

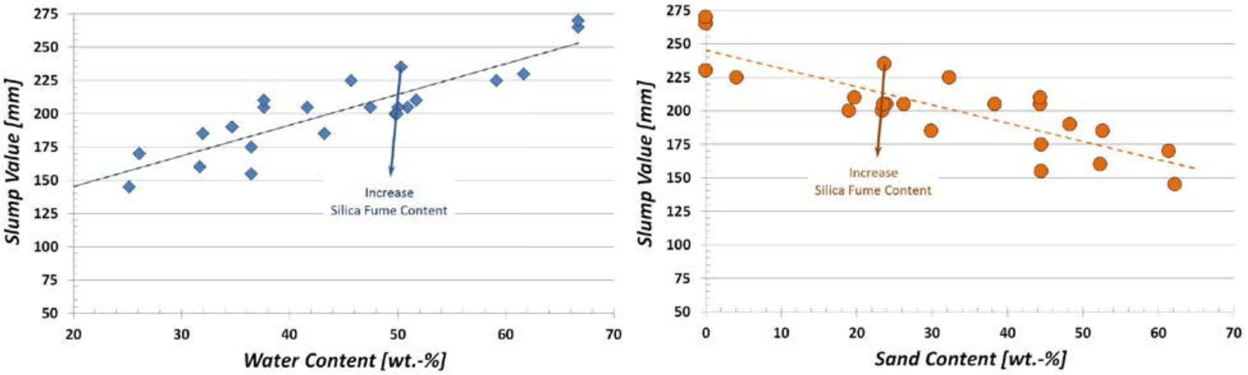

Fig. 4. Mini-slump values versus water and sand content of the mixtures (laboratory investigations).

Another important requirement for the backfill follows from the potential requirement for waste retrievability. The removal of a backfill has been investigated by NIREX. The investigations illustrate that grouts with a cube strength of 10 MPa at maximum can be removed by the water jet cutting technology [6,7] (cf. [8]). This strength limit was used to constrain the backfill composition; however, cylinders with a height and a diameter of 10 cm were proved. Two test series can be subdivided. In the course of the first test series specimens with different material compositions were investigated. The specimens were stored at temperature between 25 °C and 40 °C in sealed plastic tubes. At the time of the strength tests the so-called equivalent age of the specimens was > 90 days.

Noticeable is the dependence of the strength on the water-cement-ratio of the mixtures (Fig. 5). In addition, two mixtures with a water-cement-ratio of 4.25 but a different sand-cement-ratio were tested. The strength values are 4.5 MPa (sand-cement-ratio 3.0) and 6.3 MPa (sand-cement- ratio 7.0). This indicates that the sand content of the backfill material should be limited to guarantee the retrievability of the waste packages.

Specimens, which have strengths of less than 10 MPa, are characterized by a water-cement-ratio of > 2.8. The curve is flattening out with increasing water-cement-ratio. Accordingly, variations of the cement or water content in the range of high water-cement-ratios have only a small influence on strength. It can be assumed that high water-cement-ratios (> about 5.0) and low cement contents can result in failures of the cement stone structure. Consequently, these mixtures were not been examined further. The work focused on mixtures with a water-cement-ratio of 4.25 and the goal of the second test series was to determine the influence of the curing time or the degree of hydration on the material strength (Fig. 5).

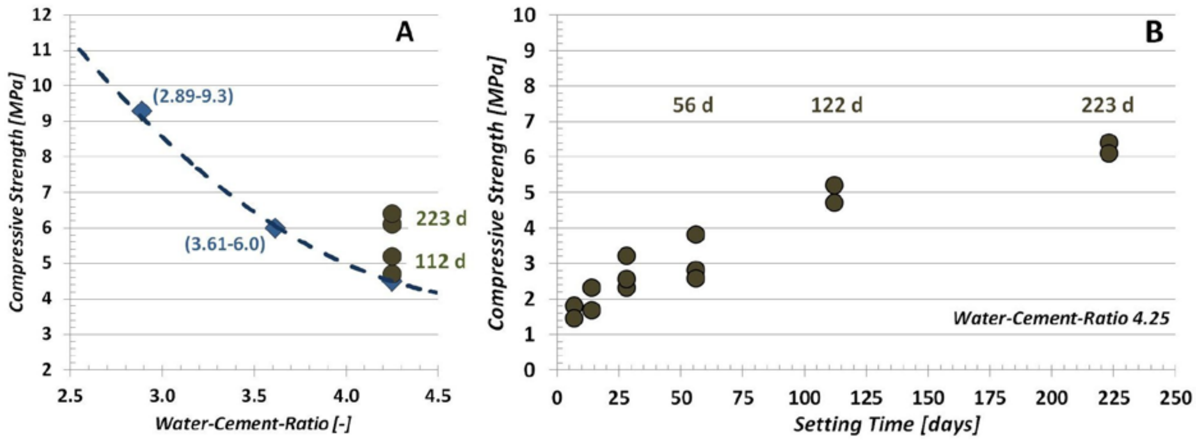

Fig. 5. Compressive strength of different mixtures – laboratory specimens. The left diagram (A) shows the decrease in strength with increasing water-cement-ratio and the right diagram (B) the increase in strength with setting time.

The strength values demonstrate the compliance with the material requirement (< 10 MPa) even after long curing times. Furthermore, the retrievability constraint was validated on a large number of specimens by destroying them with a hammer and a chisel. All the specimens were broken without excessive force. Based on these findings a reference backfill composition was defined, which is described in the Table I.

TABLE I. Composition of the reference backfill material in the units wt.-%, L/m³, vol.-%, and kg/m³. The water-cement-ratio is 4.25. The mass ratios between sand and cement, and silica fume and cement are 2.00 and 1.18, respectively. The volume related contents were calculated with density values of 3000 kg/m³ (cement), 2210 kg/m³ silica fume, 2650 kg/m³ river sand, and 1000 kg/m³ tap water. Entrapped air pore contents of 1.0[1] vol.-% and 2.0[2] vol.-% are assumed according to the results of laboratory measurements.

	[wt.-%]	[L/m³]	[kg/m³]	[L/m³][1]	[kg/m³][1]	[L/m³][2]	[kg/m³][2]
Cement	11.87	56.8	170	56.2	169	55.7	167
Silica Fume	13.95	90.6	200	89.7	198	88.8	196
Sand	23.74	128.6	341	127.3	337	126.0	334
Air Pores	–	–	–	10.0	0.0	20.0	0.0
Tap Water	50.44	724.1	724	716.8	717	709.6	710
Sum	100.00	1000.0	1435	1000.0	1421	1000.0	1407

According to the average crystal water content of the hydration products (about 20 wt.-%), it is generally assumed that for every kilogram of a Portland cement, about 0.25 kilogram of water is needed to fully complete the hydration reactions. The water-cement-ratio of the reference backfill material is 4.25. Due to the limestone content, a CEM II/A-LL fixes less water than a Portland cement. Consequently, the backfill has to contain a high amount of pore solution. The pore solution was squeezed out of the specimen that cured one month at room temperature in a pressure device. The analytical results confirm the common knowledge that the concentration of the cations decreases in the order K^+ (111 mmol/l), Na^+ (26 mmol/l, and Ca^{2+} (9 mmol/l) [10]. The chloride content was very low (< 25 mmol/l) and the determined pH-values are 9.3 and 9.5.

As a result of the low amount of gas-filled pores and the high amount of pores solution the thermal conductivity of the backfill most depends on the heat flow in the pore solution and bridges of solid components. The thermal conductivity of water is about 0.644 W/(m·°C) at 50 °C and the thermal conductivities of solids are significantly higher. First small scale tests with the transient plane source method in a heated cabinet show that the thermal conductivity of the backfill material increases with temperature. The thermal conductivity is about 1.46 W/(m·°C) at 50 °C.

Evaluation of the changes in volume

By laying down precise limits for the material composition and defining a reference backfill material, it was possible to estimate the volumetric changes and the porosity of the backfill. Volumetric changes of building materials are caused by shrinkage and temperature changes. Due to the high backfill volume (approx. 85 m³) and the length of the backfill sections (approx. 30 m), these processes must be regarded.

So-called plastic shrinkage occurs due to a loss of moisture from the surfaces of fresh materials. This loss may be in form of surface evaporation or moisture loss caused by absorbent materials. The backfill sections of the galleries will be separated from the ventilated mine workings by the formwork. The formwork will limit the air motion, and the moisture transport. An air volume of 85 m³ is capable of taking up an amount of water of approximately 1.37 kg, considering an initial relative humidity of 50 % and a temperature of 30 °C. Compared with the water content of the backfill (cf. Table I), this amount of water is relatively low.

Currently, it is assumed that the pore space of the gallery lining will become dry due to the ventilation of the galleries. The dry pore space can be saturated during and after the backfill process. However, practical experiences of the classical concrete work illustrate that this loss of water can be significantly reduced by a moistening of the surfaces. In the case of the backfilling of galleries containing heat-generating waste, it can be necessary to realize a moistening of the ambient air. As a result of the high water content of the backfill mixture and the variety of measures available to reduce a water loss, plastic shrinkage is assumed to be negligible.

The temperature of the fresh grout depends on the temperature and the heat capacity of the raw materials, the ambient temperature at the mixing plant as well as on the measures that are implemented to control the grout temperature. To gain an impression of the resulting temperature changes, Fig. 6 shows the temperature of a fresh mixture in the course of a production period of one year. The values were registered during the backfilling of openings in the Morsleben repository (Germany, Saxony-Anhalt). In this case no measures were taken to control the temperature of the backfill. The range is from 10 °C to approximately 35 °C. Lower temperatures of the mixture can be excluded. In this case, the mix water and/or the aggregate are warmed due to the risk of freezing. Fig. 6 illustrates that the temperature of the backfill material depends above all on the ambient temperature even if a backfill material with an increased cement content (328 kg/m³) is produced.

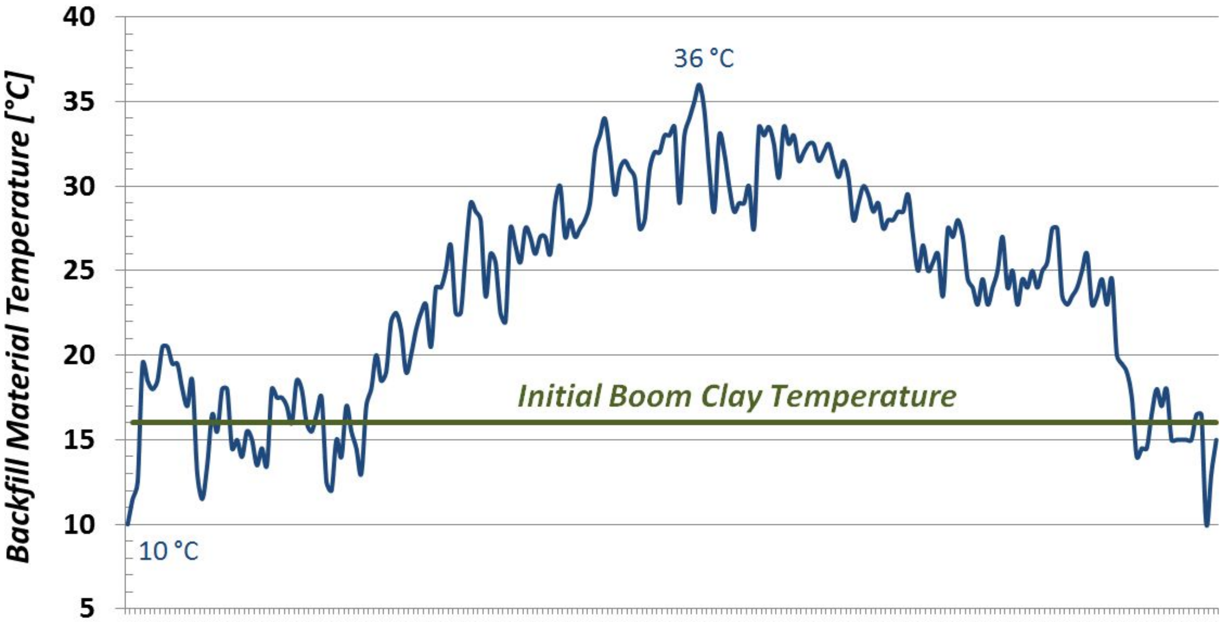

Fig. 6. Temperature change of a fresh backfill material in the course of a production period of one year (blue line). The green line shows the initial rock temperature of the Boom Clay.

In particular, three thermally induced causes of volumetric changes can be distinguished:

1) the long-term adaptation of the backfill temperature to the mine or rock temperature,
2) the temperature increase and decrease due to the development of hydration heat and
3) the temperature rise caused by the generation of decay heat from high-level waste (category C).

The hydration heat of the backfill was calculated according to the cement composition. Leaving aside the influence of the silica fume, the value is about 81 MJ/m³. The backfill heat capacity of 2.38 kJ/(kg·°C) or 3353 kJ/(m³·°C) results from the mix composition and density (cf. [9]). Under adiabatic conditions this hydration heat results in a temperature rise of 24 °C. In the case of the backfilling of category C galleries, the heat flow from the supercontainers must be taken into account, which results in temperatures of up to 70 °C. In addition the calculations of the length and volume changes consider a temperature of the Boom Clay of 16 °C.

The estimations use the Eq. 1, with σ_T the thermal induced stresses, α the thermal expansion coefficient, E the Young's modulus, t_P the placement temperature, t_H the temperature increase caused by hydration heat, and t_C the long-term continuous temperature. Since the influence of the hydration-dependent Young's modulus is not considered, the results are length changes. The calculations of this study used a coefficient α of $15 \cdot 10^{-6}$ 1/°C. The results are summarized in Table II.

$$\sigma_T = \alpha \cdot E \cdot (t_P + t_H - t_C) \qquad \text{(Eq. 1)}$$

TABLE II. Length changes of the backfill material as a result of the temperature changes. The values for the axial direction consider a total length of the backfill section of 30 m. The values for the radial direction consider the maximum distance between the supercontainers and the tunnel liner (0.8 m)

Temperature development	Category B waste		Temperature development	Category C waste	
	axial	radial		axial	radial
10 °C → 34 °C (+24 °C)	+10.8 mm	+0.29 mm	10 °C → 70 °C (+60 °C)	+27.0 mm	+0.72 mm
34 °C → 16 °C (-18 °C)	-8.1 mm	-0.22 mm	20 °C → 70 °C (+50 °C)	+22.5 mm	+0.60 mm
30 °C → 54 °C (+24 °C)	+10.8 mm	+0.29 mm	30 °C → 70 °C (+40 °C)	+18.0 mm	+0.48 mm
56 °C → 16 °C (-40 °C)	-18.0 mm	-0.48 mm	70 °C → 16 °C (-54 °C)	-24.3 mm	-0.65 mm

Cement hydration generates heat and results in a decrease in the total volume of the solid and liquid components of a mixture, because crystal water requires less space than free water in a solution. Assuming that the cement chemically bound approximately 20 wt.-% water and the density of the crystal water is 1.250 g/cm³, this chemical shrinkage amounts to 6.7 liters/m³, corresponding to 66.9 mm/30 m or 1.8 mm/0.8 m. However, the build-up of crystalline structures can significantly limit the influence of the chemical reactions on the bulk volume. In addition to the entrapped air (about 2 vol.-%), this difference of chemical and autogenous shrinkage generates gas-filled pores (< 0.7 vol.-%). At the end of cement hydration, the pore volume filled with residual solution is about 67.6 vol.-%.

With the aim to gain a more detailed insight into the material behavior and the development of the backfill properties, mock-up tests were carried out.

Mock-up Tests

The main goal of the mock-up tests was to verify the feasibility of the backfill process by filling Plexiglas tubes with backfill material. The backfill was mixed with a stationary pan mixer which has a capacity of 100 liters. A high-shear hand mixer was used in a last mixing step to enhance the dispersion of the silica fume. A screw pump transported the mixture through a 10 m long flexible pipeline (1.0 inch). Two Plexiglas tubes, which had an inner length of 2 m and inner diameter of 0.5 m, were filled with grout. This tube length corresponds to a backfill section in the galleries of 12 m and the tube diameter to a diameter of the galleries of approximately 3.0 m. The hollow cylinder, which was filled first, had a volume of approximately 425 liters. In the second tube Plexiglas plates were inserted with glue corresponding to the surface of the concrete floor in the disposal galleries. Two tubes (diameter 0.3 m, length 0.65 m) were fixed as models of supercontainers on this floor construction. The filling volume was about 325 liters. At the current stage of planning, a main injection tube will be installed on the lower face of the concrete floor. The grout will fill the galleries from the back on. The air will flow through a venting at the top of the front formwork. The same configuration was chosen for the Plexiglas tubes.

The flow rate ranged between 3 liters and 5 liters per minute and the mix temperature was about 23 °C. It was completely unproblematic to pump the grout. Before the start of the experiments, during the break between the tests, and after the end of the tests, the pumping was stopped several times. It was very easy to continue the pumping after the breaks. No unusual high pump pressures were necessary to initialize grout flow. The pressure drop due to friction in the pipeline did not change during the backfill tests. The increase in the grout pressure in the pipeline results from the rising filling level in the tubes (Fig. 8).

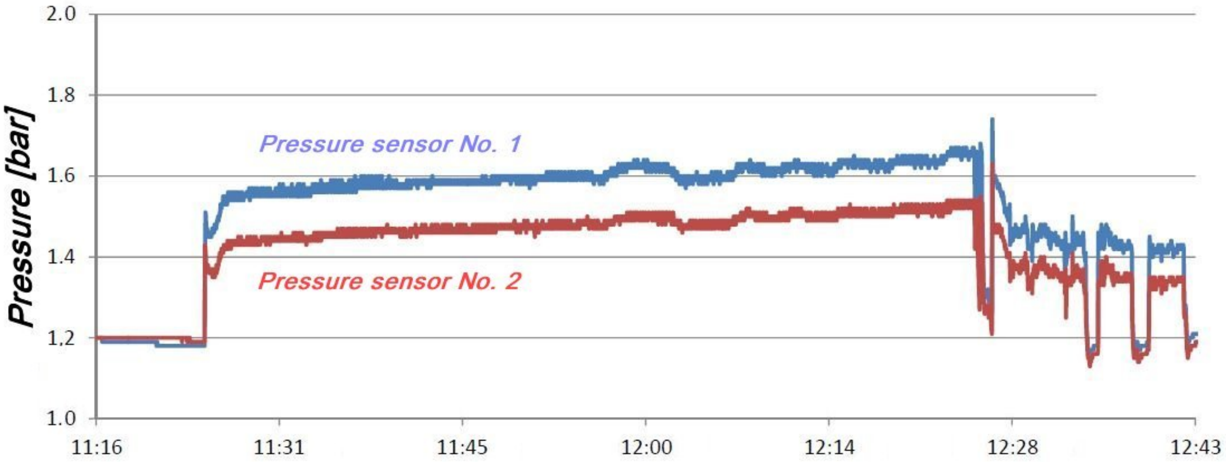

Fig. 8. Grout pressures in the pipeline during the backfilling of the second tube. The axis of abscissas shows the time in hours and minutes.

The tests prove that the backfill spreads in the tubes with a low flow angle. Fig. 9 shows the second tube after the floor construction was completely flooded with grout. The Fig. 10 illustrates a decrease of the flow angle as a function of the height of the grout surface.

Both tubes were completely filled with the backfill material, however, a low amount of bleed water and some waves developed during the first two mix batches of the first test due to a failure of the high-shear mixer. The resulting air voids and the bleed water moved to the vent opening and eventually left the tube. Accordingly only small air pores could be observed on the backfill surface. During the hardening process the temperature of the backfill in the first tube increased up to 15 °C. The time course of the temperature decrease was used to estimate an adiabatic temperature rise of the backfill material. This correction can be graphically described as a counterclockwise rotation of the temperature curve around the starting point until no maximum value is visible and temperature reaches a plateau. The inferred value is 21 °C and is almost as large as the calculated value (24 °C).

Fig. 9. View on the front plate of the second Plexiglas tube with the vent opening. The backfill pipeline ends on the opposite front plate.

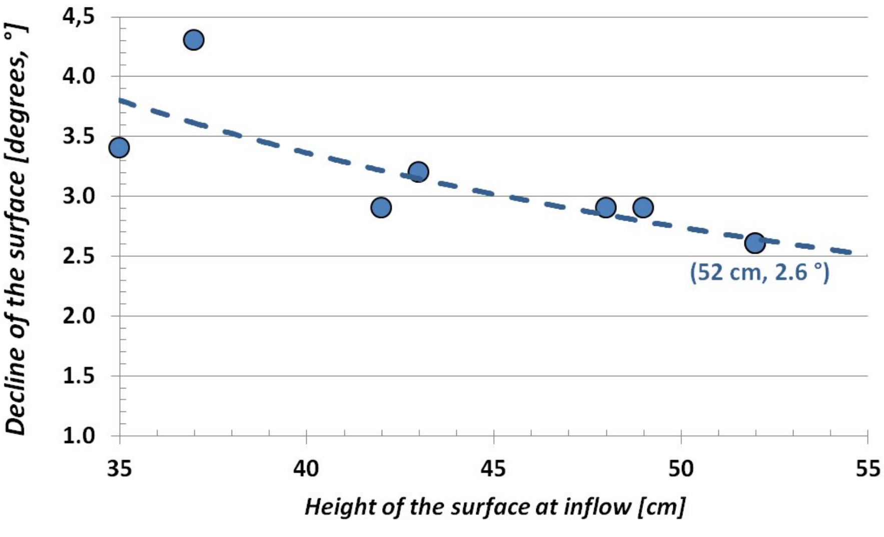

Fig. 10. Decline of the grout surface (flow angle) in dependence of the height of the grout surface at the inflow side. The flow angle decreases and the final value is about 2.5 °.

On the surface of the backfill no shrinkage cracks were observed. Four cores of the backfill were drilled 48 days after the backfill tests had been carried out. The vertical drillings were carried out along the top of the tubes and extended to the lowest part. The cores were gained in one piece and – upon surface inspection – do not show any cracks or inhomogeneities (Fig. 11). One core was cut wet into pieces to determine the density and the porosity of the backfill.

Strength tests and the further visual inspection of the backfill required the removal of large parts of the Plexiglas cover so that the backfill dried. As a result of the water evaporation, small cracks were observed on the lateral surfaces. Moreover, small air pores, in particular at the top of the cylinders, came into view (Fig. 12).

The samples of the core were stored several weeks in potable water. On the basis of the initial weight and the weight loss during the storage in a heated cabinet, a porosity of 64 % was calculated with the exception of the sample with the upper surface of the backfill cylinder (67 %). This higher porosity is explained by a higher amount of entrapped air pores which rose to the surface during the filling process (cf. Fig. 12). However, a segregation of sand particles could as well contribute to the difference in porosity.

Fig. 11. Drill cores (diameter 10 cm) of the backfill tests illustrate the homogeneity of the backfill material. According to visual inspection, density and porosity measurements the upper parts of the cylinders have a slightly increased air pore content.

Fig. 12. Air voids at the top of the backfill cylinder. The small cracks are caused by the drying of the backfill after the removal of the Plexiglas.

Qualitative strength tests with a hammer and a chisel as well as an electric concrete breaker were carried after a setting time of 41 days, 48 days, and 84 days. It was easy to remove the material. In addition, laboratory tests showed that specimens, stored up to 253 days, can easily be destroyed with a hammer and a chisel. No excessive force was necessary to penetrate the chisel into the backfill. Fig. 13 shows a snapshot taken during the work.

Fig. 13. Front face of the second backfill cylinder with the supercontainer models. Fragments of the backfill were chiseled out by hand and with a small electric concrete breaker.

DESIGN OF THE BACKFILL SYSTEM

Due to the positive findings of the rheological investigations, pressure drops and pressure profiles along the backfill pipeline of the repository were calculated. The calculations were made based on the assumptions that the maximum flow rate is 25 m²/h and that pipelines with a diameter of 80 mm (DN 80), 100 m (DN 100) or 125 mm (DN 125) will be used. The Fig. 14 shows an example of the pressure profile. The flow velocity of the backfill is about 1.4 m/s at maximum in a DN 80-pipeline. In this range, the conditions are met for a laminar flow of the backfill. A flow time of 5 hours would be exceeded as the flow rate would fall below 20 m³/h in a DN 125-pipeline. Accordingly, the assumption of a total flow time of 5 hours is correct, which was considered during the laboratory investigations.

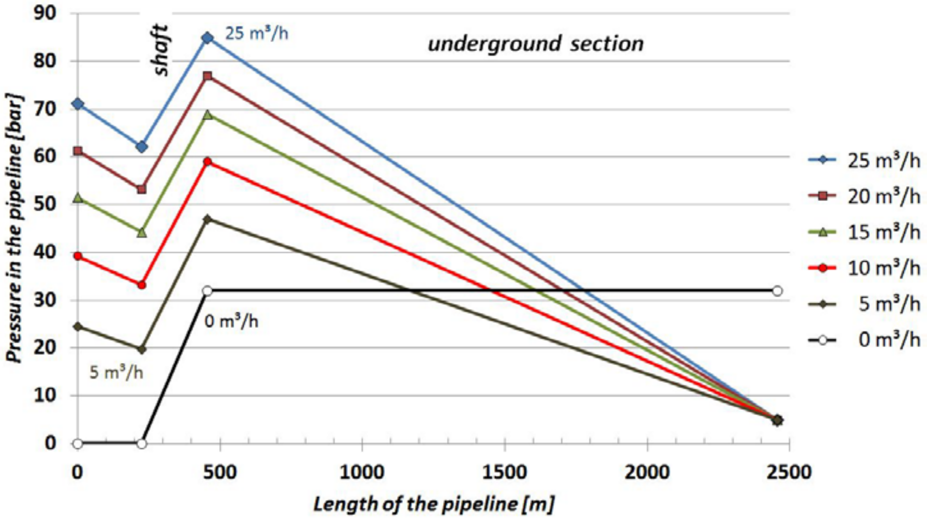

Fig. 14. Pressure profile along a DN 100-pipeline in dependence of the flow rate.

It can be concluded that standard equipment, such as tanks, pumps, pipelines, pig trap stations, and damper can be used for the installation and operation of the backfill system.

CONCLUSIONS

The backfill tests demonstrate that the mixture can be transported via pipelines and has the capability to completely fill the backfill sections. Cracks may occur in the galleries with category B waste due to the cooling of the backfill material, which is caused by the discharge of hydration heat. In addition, there is a risk of crack formation more or less perpendicular to the axis of the galleries with category B and category C waste as a result of autogenous shrinkage. These cracks were not observed during the laboratory and backfill tests because of the limited length of the specimens (≤ 2 m). However these cracks will not influence the functionality of the backfill and the material properties will still be in conformity with the requirements.

The high porosity of the backfill is favorable for the storage of gas. If the results of temperature field calculations suggest an increase in the thermal backfill conductivity, laboratory tests proof the suitability to replace some of the silica fume with iron oxides and to increase the sand content [11]. However, in this case more research shall be needed.

Different techniques were used to investigate the strength of the backfill. The test results confirm the conclusion that the backfill can be removed by general equipment. Consequently, the fundamental requirement for the retrievability of the waste packages is ensured. In summary, the tests demonstrate the feasibility of backfilling the galleries in conformity with the requirements.

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