NUCLEAR AND INDUSTRIAL ROBOTICS, REMOTE SYSTEMS AND EMERGING TECHNOLOGIES

TRAVEL TO PHOENIX, AZ FOR

THE WORLD'S LARGEST Radioactive Waste & Material CONFERENCE

Nuclear and Industrial Robotics, Remote Systems and Emerging Technologies

Join us at WM2018, the 44th annual Waste Management Symposia, to participate in a forum for discussing and seeking safe and cost effective solutions to the management and disposition of radioactive wastes and the decommissioning of nuclear facilities. Don't miss the opportunity to exchange ideas, technical information and solutions with 2,000 nuclear waste industry delegates from more than 35 countries.

The WM2018 conference will feature the development and application of robotics and sensing to overcome radioactive waste management challenges. Robotics and sensing are being developed to address unique and routine needs in the nuclear sector. These technologies help increase safety, reduce worker exposure and decrease costs. This rapidly evolving work will be showcased through topical sessions and extensive displays of equipment, representing industry and government exhibitors, which will be demonstrated on the show floor.

WM2018 will deliver over 600 papers and 40 panel discussions in over 130 technical sessions which will be complemented by the industry's largest exhibition of nearly 200 companies. The exhibition will feature a dedicated space to showcase the latest in the robotic technology as well as host product demonstrations.

Panel, Poster and oral paper topics specific to the featured theme include:

Nuclear and Industrial Robotics, Remote Systems and Emerging Technologies

This topic will focus on all aspects of the use of robotics, remote systems, sensing, and tools used in the industrial and nuclear industry, including needs, problem statements, research and development. Abstracts are encouraged that discuss technology maturation, utilization, testing and verification, best practices, lessons learned, knowledge management and trends in robotics and remote systems, applications, facilities, use in emergency preparedness or response and recovery actions and the ability to withstand exposure to radioactive contamination or ionizing radiation. This topic will organize various oral sessions and related Topics, such as:

- Role of Robotics in the Management of HLW, SNF/UNF and Long-lived Alpha/TRU
- Remote System Handling and Robotics for Commercial Nuclear Power Plants
- Application of Innovative D&D Technologies Including Robotics and Remote Technologies

COMPREHENSIVE Technical Program and Exhibition ON DECOMMISSIONING & RADIOACTIVE WASTE MANAGEMENT

WM2018 will include papers and panels describing research, development and operational experiences over the complete spectrum of nuclear waste activities. Detailed Topic descriptions are found on our website and categorized into 10 general Tracks:

TRACK 1	Crosscutting Policies and Programs and the Robotics Theme Topic
TRACK 2	High-Level Radioactive Wastes, Spent Nuclear Fuel/Used Nuclear Fuel and Long-Lived Alpha/Transuranic Radioactive Waste
TRACK 3	Low-Level, Intermediate Level, Mixed Waste, NORM, & TENORM
TRACK 4	Nuclear Power Plant Waste and On-Site SNF/UNF Management
TRACK 5	Packaging and Transportation
TRACK 6	Decontamination & Decommissioning
TRACK 7	Environmental Remediation
TRACK 8	Communications, Education and Training
TRACK 9	Special Topics Including Safety, Security, & Safeguards
TRACK 10	Miscellaneous

WM2018 will display the industry's largest exhibition, showcasing all aspects of products and services related to the nuclear waste industry and the 2018 Theme. Areas of interest include; remote/robotic handling, protective clothing, hazardous waste storage, transportation, diagnostic instrumentation, engineering design and construction, environmental laboratories, decontamination and decommission and environmental remediation. In addition, there will be a dedicated Robotics space to demonstrate the latest technology of professionals and academia. For more information, please visit **www.wmsym.org/WhyExhibit**

WMS is a non-profit organization whose mission is to provide education and an information exchange on global radioactive waste management. Over 100 scholarships and $3 million dollars has been contributed to students and education. Please visit **roygpost.org** for further scholarship details.

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Backfilling of Geological Disposal Facilities – Development of Optimized Backfill Material
18146

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Backfilling and sealing are integral parts of the multi barrier concept of a geological disposal facility (GDF). General tasks of the backfill are to stabilize openings, to minimize the void volume that can be filled with water or brines, and to ensure a favorable chemical milieu with regard to the overall disposal system. Depending on these functions and the conditions provided by the GDF design and the safety concepts, backfilling materials have to comply with a wide scope of requirements.

ONDRAF/NIRAS the competent Belgian organization for radioactive waste management proposes to build a GDF in a poorly indurated clay host rock. Low- and intermediate-level radioactive waste (B-waste) will be conditioned in concrete monoliths B and high-level, heat-generating waste (C-waste) in so-called Supercontainers (SC). The SCs consist of overpacks embedded in concrete and a steel envelope. The two types of waste packages will be disposed of in separate fields of the future GDF.

In the framework of a technical support project with ONDRAF/NIRAS, DBE TECHNOLOGY GmbH has developed reference backfilling materials. It is planned to backfill the remaining voids inside the disposal galleries stepwise after the emplacement of a specified number of waste packages. As the space underground is restricted and to generally minimize operational activities underground, the preferred concept is to mix the backfill above ground and to pump the mixture via a piping system into the backfill segments. Consequently the backfill material has to remain in a flowable condition for the time needed for the transport process. After filling the segments, the backfilling material shall harden without swelling or significant shrinkage to homogenous bodies. Additionally, according to the current ONDRAF/NIRAS retrievability concept, the strength of the backfilling bodies has to be low enough to allow a later excavation of waste packages should that be required.

Initially, these general tasks suggest the development of a universally usable material for the backfilling of all galleries. Nonetheless, the different characteristics of the B- and C-waste packages and differences in the designs of the emplacement fields require the specification of individual catalogues with many common, but also several different material requirements for the development of backfilling material for B- and C-waste disposal galleries.

The requirement of chemical compatibility makes it necessary to use a cement-based backfill and all potential mixtures must meet the criteria for hydraulic backfilling. However, particularly high demands have to be specified for the time of workability and flowability of the backfill of the C-waste field due to its large extension resulting in pipeline lengths of up to 4000 m.

Other deviating requirements for material properties of the two backfill types originate from the long-term behavior of the two waste types. For instance, the pore volume of the B-waste backfill must be large enough to allow gas flow and thereby minimize a possible gas pressure built-up, due to the degradation of organics. In contrast, a lower porosity is favored to achieve a higher thermal conductivity for a better dissipation and removal of the C-waste decay heat. Moreover, for the C-waste backfill a minimum pH value was prescribed with the objective to guarantee a long-term passivation and corrosion resistance of the SC steel surface.

After defining the requirement catalogues, the next step was dedicated to the selection of suitable raw materials based on the knowledge of technological properties of available high-quality materials. For instance, Portland limestone cement was selected as the binder of the B-waste backfill and a Portland cement for the C-waste backfill to achieve the required high pH value in this waste field. Another example is the use of sand aggregate, which is allowed in the B-waste field, while only limestone powder and aggregate were considered for the development of the C-waste backfill to safely prevent alkali-silica reactions at elevated temperatures.

Usually, the time span of workability of low-porosity Portland cement mixtures is limited, whereas the backfilling of the voids in the C-waste field require an exceptional long potlife. This example demonstrates that different requirements often have contrary consequences for the material selection and vice versa. Consequently, one focus of the backfill development was to identify compositional ranges that guarantee the respective material property. Finally, a combination of the individual „conformity fields" results in the optimal solution for the standard operating conditions as well as a compositional range that guarantees compliance with the required material specifications. These interrelations and the general strategy used to reach the optimal solution will be demonstrated for the two development lines of the B- and C-waste backfill. The principle strategy can be adapted to many underground repositories and conventional mines.

Backfilling of Geological Disposal Facilities – Development of Optimized Backfill Material – 18146

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ABSTRACT

In Belgium, low- and intermediate-level waste (B-waste) will be conditioned in concrete monoliths and high-level waste (C-waste) in so-called Supercontainers (SCs). The Belgian radioactive waste management program has focused on the disposal of these waste types in two emplacement fields of a geological disposal facility (GDF). When the disposal waste packages (DWP) have been emplaced, backfilling of the galleries is supposed to be carried out in order to stabilize the galleries, to reduce voids, to guarantee a favourable chemical milieu with regard to the retention of the radionuclides, to minimize a possible gas pressure build-up, to dissipate radioactive decay heat and to enable good conditions for a potential retrieval of the DWP. The current reference solution is to mix the backfill at the surface and then to pump the mixture through pipeline distribution systems into the underground structures.

The catalogue of backfill material requirements comprises common, but also different requirements due to the characteristics of the B and C waste packages and differences in the backfilling systems. It was found that two backfill material recipes have to be developed. Different requirements, such as high porosity (low strength and low gas threshold pressure) and high thermal conductivity have contrary consequences for the material composition and vice versa. In addition, during backfill production quality variations of the raw materials that influence the backfill material properties can occur. Different lengths of the delivery pipeline may require adjustments of the material composition. Consequently, one focus of the development programs was to identify compositional ranges that guarantee the respective material property. A combination of the individual “conformity fields” results in optimal solutions for the standard operating conditions as well as a compositional range that guarantees compliance with the required material specifications.

INTRODUCTION

About 70% of the radioactive waste produced in Belgium arises from the nuclear industry. The remaining 30% of waste is generated in the course of research work, radioisotope production by the National Institute for Radioisotopes, the use of radionuclides in medicine, industry and in private laboratories, and the Euratom Institute for Reference Materials and Measurements. The conditioned waste types are subdivided into the categories A, B, and C. Simplified, low- and intermediate-level waste with a half-life of less than 30 years can be assigned to A waste. A waste drums are embedded in cementitious mortar, creating cubic monoliths. Conditioned A waste presents a risk for man and the environment on a timescale of hundreds of years. The Belgian government decided in favor of a near-surface disposal facility for this waste type.

Low- and intermediate-level radioactive waste with a half-life of more than 30 years (B-waste) will be conditioned in concrete monoliths and high-level, heat-generating waste (C-waste) in so-called Supercontainers (SCs). The SCs consist of the waste canisters in carbon steel overpacks embedded in Ordinary Portland Cement buffers and a stainless steel envelope (cf. [1]). The risk that B&C waste present extends hundreds of millennia and a GDF seems to be the only management solution capable of protecting man and the environment. ONDRAF/NIRAS proposes poorly indurated clay as a reference host rock formation (working hypothesis) and performs RD&D to develop a disposal facility (cf. [2]).

Backfilling and sealing are integral parts of the multi barrier concept of a GDF. In the framework of a technical support project, DBE TECHNOLOGY GmbH has developed reference backfill materials on behalf of ONDRAF/NIRAS. The development program considered the GDF design, the type and design of the backfilling system, the planned workflows, and the objectives of the backfilling measures. The aim of this publication is to describe the conditions of backfilling and the strategy used in material development.

GDF DESIGN AND OPERATIONAL ACTIVITIES

According to the current plans, the underground openings will be erected at a depth of 200 m, 400 m or 600 m. One shaft serves to transport the DWPs and a second one is designed for staff and material transport. A connecting gallery is located in a central service area, which is separated into the shaft zone and two seal zones at the entrances of two emplacement fields. It is planned to dispose of the two types of waste packages containing B waste and C waste in separate fields. Two parallel access galleries run through the middle of each emplacement field and connect the 400-m-long dead-end disposal galleries. The length of the access galleries depends on the number of disposal galleries, the spacing between these galleries, and their distance to the shaft zone. The minimum distance between adjacent disposal galleries for non-heat-generating waste disposal was set at 50 m. Thermal power of heat-generating waste requires a distance of 120 m between the galleries. All galleries are located on a horizontal plane.

During a first construction phase, the shaft zone and the galleries of the B waste field will be excavated. At the end of the stepwise performance of disposal, backfilling, and closure operations, the second emplacement field will be excavated. After the disposal of C waste and backfilling of the disposal galleries, the GDF will be closed.

The current reference solution is to mix the backfill at the surface and to pump the mixture through pipeline distribution systems into the underground structures. During the backfilling programs, the lengths of the horizontal pipeline sections will shorten significantly and consequently the back pressure, which arises due to the friction losses during the pump process. Since this fact can lead to problems with regard to the operation of the backfilling systems, modifications are considered, for example the installation of valves and/or pipeline loops (“throttle lines”). An alternative or supplement to the technical measures is to adjust the flowability of the backfill materials. This is usually done by controlling the amount of water or superplasticizer. The feasibility of these possibilities should also be investigated.

OBJECTIVES OF BACKFILLING WITH REGARD TO LONG-TERM GDF PERFORMANCE

Objectives of the backfilling 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
(3) reducing the voids in the GDF that could be filled with water,
(4) ensuring a favorable chemical milieu with regard to the overall disposal system,

(5) providing a storage volume for gas generated in the disposal galleries, thus limiting gas pressure build-up, and
(6) dissipating the decay heat of heat-generating waste.

Despite the fact that the backfill supports the gallery lining, according to the current ONDRAF/NIRAS retrievability concept, the strength of the backfill material has to be low enough to allow excavation of DWPs should that be required.

THE CATALOGUES OF REQUIREMENTS

Based on the objectives of backfilling and the conditions of use, material properties have been identified to which requirements are to be specified. Strict limiting values (“hard criteria”) and desired target values (“soft criteria”) have been set as well as the corresponding test methods. Some material properties should only be measured. It is planned to carry out the safety assessments at a later time. Different specifications result from the backfilling technique, the specific properties and the assumed long-term behavior of the DWPs. The specifications are described in the following. The numbers in parenthesis are a reference to the objectives of backfilling. The requirements for the backfill materials can be assigned to five main groups.

The first group of requirements relates to the backfill technique and the objective to obtain the highest possible filling ratio (1 - 3, 6). This requires a sufficiently long and good flowability of the backfill materials. The specification refers to spreading tests with a cone according to EN 459-2 [3]. The cone was placed on a glass plate and filled with suspension without interruptions. After a short wait, the cone was lifted vertically upwards, so that the sample spreads on the plate to form a circular “cake”. The average diameter of this cake is called slump. The limit values of slump (≥ 21 cm B waste backfill, ≥ 25 cm C-waste backfill) refer to the laboratory mixer. It can be assumed that the material has a better flowability under in-situ conditions due to the high shear during the pipeline transport. The different limit values for the slump result from the fact that the maximum pipeline length of the C waste emplacement field is considerably longer. In order to avoid unusual high pump pressures higher demands have to be specified for the flowability of the backfill material of the C waste field. The required time of workability results most of all from the backfilling time of the segments. Accordingly, the requirement of the workability time (> 5 hours) is equal for the B waste field and the C waste field.

Throughout the flow process and thereafter, no separation may occur between particles of different sizes or densities (segregation) and between the solids and the liquid phase (no bleeding) in order to guarantee an unproblematic pump process and to obtain homogenous backfill bodies. For the investigation of the bleed process samples were filled into transparent cylinders. The openings of the cylinders were sealed with plastic sheets and adhesive tapes. With the aim of visually inspecting the grain distribution (segregation resistance), the surfaces of cylinders were ground with abrasive paper or cylinders were cut along their longitudinal extent. Moreover, fractured surfaces were investigated.

The second group comprises chemical (4) requirements, because the backfill materials have to be chemically compatible with the host formation and any other component of the disposal system, like the gallery lining and the DWPs. Chloride- and sulfur-containing substances (sulfates, sulfides) must be minimized due to the risk of initiating corrosion processes. A minimum pH value was prescribed for the C-waste backfill with the objective to guarantee a long-term passivation and corrosion resistance of the SC steel surfaces. Organic substances and their degradation products have the potential for complex formation, which increases the mobility of radionuclides. Furthermore, the production of carbon dioxide can initiate the flow of contaminated waters due to gas pressure build-up. Consequently, the organic content of the backfill is heavily limited.

The third group includes mechanical properties and the development of mechanical stresses (2). After filling the segments, the backfill material shall harden without increase in volume or significant shrinkage to homogenous bodies. In addition, in spite of a satisfying hardening behavior, the strength of the backfill has to be low enough to allow potential excavation of DWPs in order to prejudice the potential retrieval of the waste. Experiments demonstrated that backfill with a compressive strength of 10 MPa can be removed [4,5]. Strength values were determined according to EN 12390-3 [6] of cylinders with a height and a diameter of 10 cm. The mechanical destructibility was also tested with a hammer and a chisel, milling machines, handsaws, hammer drills, and core drills.

The fourth group was specified with regard to the gas flow in the pore space of the backfilling materials (1, 5). For instance, the pore volume of the backfill materials must be large enough and the gas threshold pressure low enough to allow gas flow and to thus minimize a possible gas pressure build-up. In addition, a high porous backfill might be envisaged as it can provide a storage volume for gas generated in the GDF. A higher porous backfill is envisaged for the B waste field, for which the gas generation is expected to be more significant than for the category C waste.

The fifth group relates to thermal properties. The temperature development due to cement hydration should be limited in order to reduce the formation of thermally induced cracks. The material of the C waste field must have a thermal conductivity of more than 1.0 W/(m· K) and a sufficiently low thermal expansion coefficient. Furthermore, it has to be thermally stable under the maximum temperature that will occur in the GDF (6).

SELECTION OF THE RAW MATERIALS

Based on the requirements for the backfill materials, requirements were specified for the raw materials, which were used as selection criteria. In addition, it was defined to use only standardized raw materials of the building industry in order to meet the requirements for the storability, the dosing capacity, and the occupational health and safety requirements. The long-term availability of the raw materials should be guaranteed. Moreover, a BENOR certificate should be available. BENOR-certified products are characterized by a pronounced quality control programme resulting in a highly stable production processes.

Especially the objective to ensure a favorable chemical milieu makes it necessary to use standard cement, for example according to EN 197-1 [7]. Slags or slag-containing materials were not used due to their sulfide content neither were coal fly ashes due to their content of organic substances. In addition, it was not allowed to add clay materials or slates. This decision restricts the selection of cements and fillers. The use of cement according to the strength class 52.5 was not allowed due to the requirement on the maximum backfill strength. In order to increase the amount of hydroxide ions (pH value), no cement with low active alkali content (na-cement) should be added to the C waste backfill.

Alkali and hydroxide ions may react with alkali-sensitive SiO_2 constituents. The consumption of hydroxide ions lowers the pH value of the pore solution. Due to the potential of alkali-silica reaction the use of quarzitic aggregate was limited to the backfill of the B-waste field. Regardless of the composition of the aggregates, the maximum grain size was initially limited to 4 mm.

Despite the fact that the use of organic admixtures has been severely restricted, it is possible to add superplasticizers with polycarboxylate ethers (PCEs). In order to minimize the addition of dissolved harmful components, only potable water can be used for mixing.

In accordance with the restrictions and the experience and knowledge regarding the influence of the ingredients on the material behavior, a Portland-limestone cement (CEM II/A-LL), silica fume (filler) and sand (aggregate) were selected as ingredients of the B waste field backfill material. The selection process of the raw materials, which should be used for the production of the C waste field backfill, considered the composition of the Nirex Reference Vault Backfill Material (NRVB). Portland cement (CEM I 42.5), limestone powders, hydrated lime, limestone, and aggregate were selected. One reason to favor calcareous products was limestone's low thermal expansion coefficient, which lowers thermal stresses of the C waste backfill material. Due to long pipeline in the C waste field, it was decided to test the suitability of PCE-superplasticizers.

DEVELOPMENT OF THE BACKFILL COMPOSITION

The time span of workability of cementitious mixtures is limited by the onset of hydration reactions. They cause an increase in the solid volume and the expense of water. The time span of workability can be extended by dosing more water, however, practical limits are set to this approach, for example due to the loss of segregation resistance, the development of bleed water, and the loss of strength development capacity. With regard to the C waste backfill material, the requirements of high porosity and low strength suggest increasing the water content; however, high thermal conductivity favors to lower the water content and porosity of the backfill. According to these examples and as Fig. 1 illustrates, different requirements often have contrary consequences for the material selection and composition.

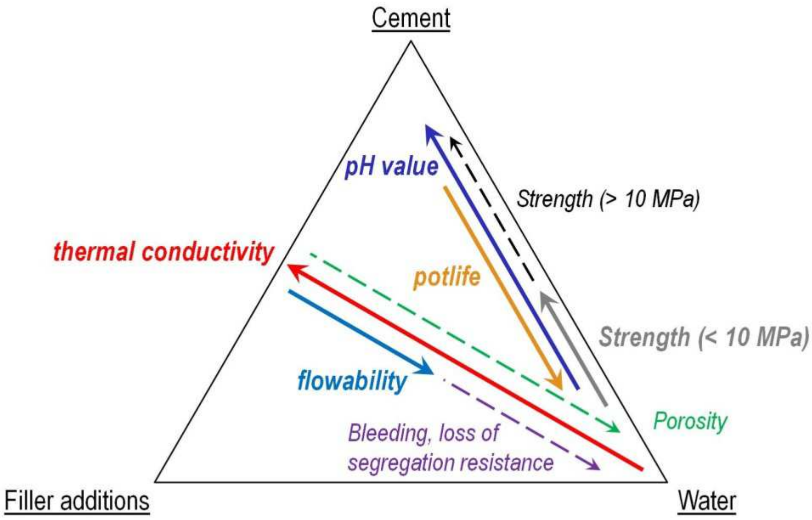

Fig. 1: Qualitative dependencies of material properties and cement-filler-water-ratios.

Another aspect that must be considered during backfill material development and use is that raw material properties affect the properties of the mixture in different ways. For example, variations in grain size and surface texture of the solids influence the flow behavior of the suspensions, whereas backfill strength strongly depends on water-cement-ratio. In order to guarantee the strength requirement, a target value of 270 kg/m³ water and an upper limit of 295 kg/m³ were specified for the concrete that was used to backfill openings of the Morsleben repository (ERAM). Up to the upper limit, the material composition can be changed in order to control the flowability of the backfill material.

Due to these facts and based on experiences, one focus of the development programs was to identify compositional ranges that guarantee the conformity with each material requirement. These ranges were also referred to as conformity fields. A combination of the individual conformity fields results in the optimal solution for the standard operating conditions. The compositional range can be used to define a reference backfill material composition.

In the following, this procedure is illustrated by the examples of the B and C waste field backfill materials. In particular, reference is made to the material requirements with fixed limits. The principle strategy can be divided into preliminary work, which includes an evaluation of the knowledge of the construction technology and practical work. The practical work can be subdivided into small-scale laboratory work, mock-up tests and large-scale in-situ investigations. The main focus of the laboratory work is material development, while the mock-up tests and in-situ investigations are carried out with the aim to prove conformity with the material requirements.

EVALUATION OF EXISTING TECHNOLOGICAL KNOWLEDGE

In the field of building material technology extensive knowledge exists about the dependencies of material properties and composition. The objective of the preliminary work is to evaluate the knowledge as well as the experience gained during the development and use of construction materials. For example, the fact is generally accepted that compressive strength of construction materials is mainly influenced by the water-cement value w/c. Cement has a specific capacity to stimulate reactive fillers. In the case of silica fume, the maximum reactive portion should be 11 % of the cement content. These dependencies were used to set minimum w/c values of 1.7 and 1.5 for the backfill materials of the B and C waste field, respectively.

The w/c value and strength are indirectly coupled together via porosity or more precisely via the number of capillary and gel pores of the cement stone. This situation allows the estimation numerous other material properties. Based on the data sets of estimated values, possible difficulties of material development can be identified early and thus taken into account in the work planning. Thermal conductivity and strength of a cement stone decrease with increasing porosity. As a result, it has been recognized that greater effort might be required to meet the requirements in the case of the backfill material of the C waste field.

LABORATORY INVESTIGATIONS

The laboratory work can be divided into three phases. The first phase is necessary when product information has not allowed a final material selection. Bleeding and flowability of raw material suspensions were tested in order to carry out this task. Despite the fact that this phase is not described in detail, test results are given to illustrate the influence of limestone fillers with different grain size on the rheological material properties.

During the second phase, fine-grain suspensions were investigated with the aim of developing mixtures that meet or at least largely meet the requirements. The third phase was carried out in order to optimize the recipes. The focus was on the investigation of mixtures with aggregate or superplasticizers. However, tests showed that the addition of superplasticizer leads to a strong increase in thixotropy. This effect is a loss of flowability due to the build-up of internal structures and occurs when shear stress is reduced. Thixotropy is coupled with an increase of yield stress and causes higher pump pressures after breaks of a pump process. Accordingly, the use of superplasticizer was initially discarded. The task of the last phase, which is currently planned for the C waste backfill material, is to complete the proofs of material requirements by means of acknowledged methods of high accuracy.

If diagrams are used for the evaluation, it is possible to represent mass fractions or ratios. Regardless of the approach the type of mixture adaptation during the backfilling process should be taken into account. Mostly, the amount of water and thus the water-solid ratio and the water-cement ratio is changed to control the flow behavior. In order to facilitate mass balance calculations, the water dosage should be coupled with a mass change of a solid raw material component. It is useful to change the amount of aggregate, due to its low water demand and the fact that the fine-grained filler particles are important for ensuring the sedimentation stability.

Differences of the following diagrams result from the fact that the fine grain contents of the B and C waste backfill material are a 3 or 4 component system, respectively. The mock-up tests of the B waste field backfill materials have already been described in [8] and are therefore not part of this publication.

B Waste Field Backfill Material

Compressive strength values showed that silica fume significantly influence strength development and final strength of the test specimens. Exceptionally long hardening times made it difficult to determine the borderline of the conformity field. Nevertheless, a minimum water-cement ratio of 3.5 was set, guaranteeing a strength of less than 10 MPa. Due to this fact, only rheological properties of mixtures with high water content were investigated.

Fig. 2 shows the borderline of bleeding and segregation resistance as a function of the water-cement ratio and the silica fume-cement ratio. The sand content was varied only in a small range between 15 wt.-% and 25 wt.-%. The diagram demonstrates that high water contents can be realized because silica fume limits bleeding due to its low sedimentation rate. The development of a sufficiently high yield stress has the positive effect that a segregation of sand can be excluded for non-bleeding suspensions. In addition, the investigations showed that a minimum water-cement-ratio of approx. 3.8 is necessary to ensure the required flowability. Mixtures with a cement-water ratio of more than 5.1 were not investigated due to the potential risk that a three-dimensional network of hydration products could not be build-up.

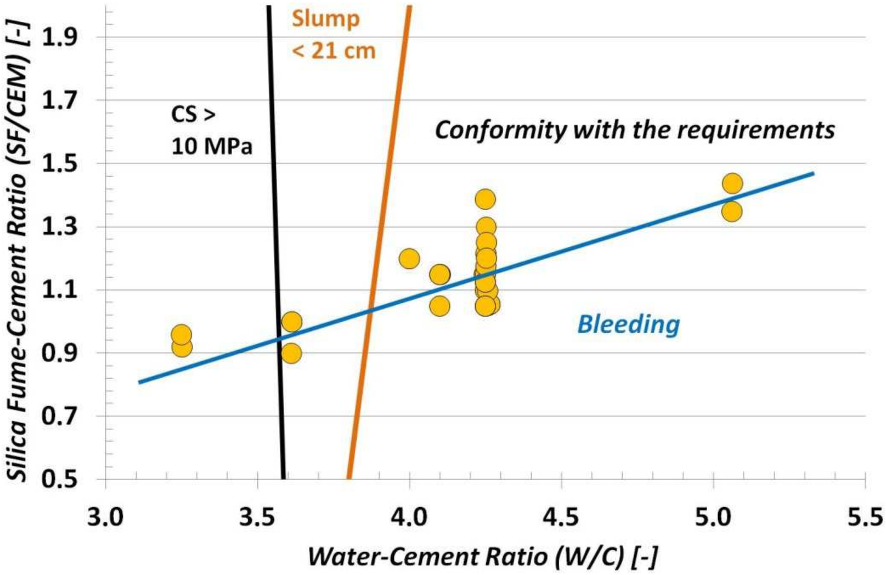

Fig. 2. Water-cement ratio and silica fume-cement ratio of mixtures and the conformity fields of bleeding, compressive strength (CS) and slump**.** In the case of non-bleeding mixtures a sedimentation of the sand was not found. Due to this fact, the diagram considers no information on the segregation resistance.

Fig. 3 shows an overview of calculated values of the adiabatic temperature increase and porosity as well as the borderline of compressive strength. The figure considers the sand component due to its significant influence on temperature, porosity and mechanical destructibility of the backfill material. Two important facts are that the temperature increase during hardening and the porosity are high over the entire range of the diagram. The low cement and in particular Portland clinker content is the main reason for the low amount of hydration and also leads to a slight shrinkage. The yellow point marks the finally selected reference backfill recipe. The mixture contains 11.87 wt.-% cement, 13.95 wt.-% silica fume, 23.74 wt.-% sand, and 50.44 wt.-% water.

A uniform and controlled backfilling process requires adjustments of backfill material flowability. In order to avoid a change of the backfill volume and mixer charges an increase of the water content should be coupled with a decrease of another mixture component. In this case, an inert filler and aggregate are taken into account in order to avoid a significant change in the binder-water or cement-water ratio. The aggregate is selected if a loss of segregation resistance is possible. In the case of the reference material, however, it is appropriate to adjust the proportion of silica fume. The orange triangles shown in Fig. 3 give an impression of how the adiabatic temperature and porosity changed when the water content is varied in steps of 10 liters or kilograms per cubic meter, with appropriate adjustment of the silica fume content. The material requirements for the hardened backfilling material are also met in the case of corrections to the flowability.

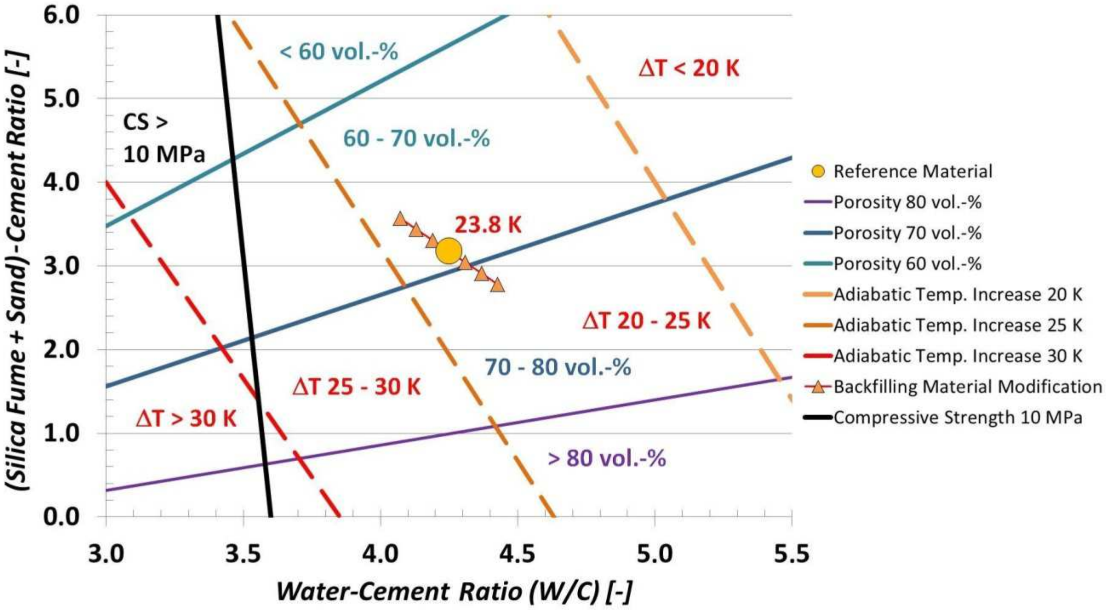

Fig. 3. Water-cement ratio and silica fume+sand-cement ratio of the reference backfill material and the conformity field of compressive strength (CS). The lines mark fields of adiabatic temperature increase and porosity. The triangles illustrate changes in the water and silica fume contents of the backfill materials. The respective distance between the triangles corresponds to an increase or decrease of the water content of 10 liters.

With the aim of estimating the gas threshold pressure, investigations were carried out on the capillary suction of the dried specimens. Low suction heights were measured corresponding to high effective capillary pore sizes and low gas threshold pressures.

The specimens of the reference backfill material could easily be destroyed with a hammer and a chisel as well as by milling and sawing. The results allow the conclusion that the backfill material could be removed by classic mining machines. Consequently, the fundamental requirement for the retrievability of the DWPs is ensured. In summary, the investigations demonstrate the feasibility of backfilling the galleries in conformity with the requirements.

C Waste Field Backfill Material

Fig. 4 shows the water-solid-ratio and the slump of test mixtures and the borderline of bleeding of fine-grained suspensions. The borderline of segregation is only valid for samples containing filler KSM 60/3 (KSM: Kalksteinmehl) and an aggregate product (maximum grain size 4 mm) of the FELS-Werke GmbH.

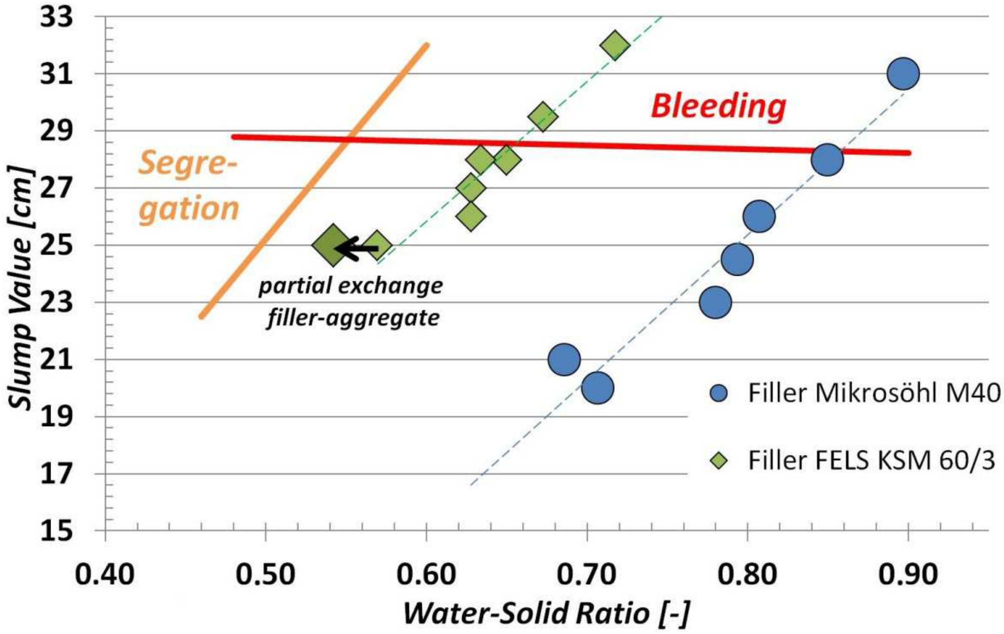

Fig. 4. Mini-slump values versus water-solid ratio of test mixtures (laboratory investigations). The red line separates the fields of bleeding and non-bleeding mixtures. The orange line is a borderline of segregation of mixtures containing filler (KSM 60/3) and an aggregate product (grain size distribution 0/4) of the FELS-Werke GmbH.

One finding is that both filler products can be used to produce non-bleeding mixtures with sufficient flowability (≥ 25 cm slump). Mixtures with filler Mikrosöhl M40 have a higher water-solid ratio with comparable slump. In order to select the best product, strength measurements were carried out. The results show that all mixtures fulfill the requirement (< 10 MPa) and that strength is strongly influenced by the water-cement ratio. The limit of 10 MPa corresponds to a w/c ratio of about 1.4. Due to the fact that higher levels of hardening are to be expected under in-situ conditions and that the addition of aggregate should increase strength, a minimum w/c ratio of 1.5 was set. In addition, the specimens could easily be sawed, broken and milled. A swelling of specimen was not detected, only a very slight shrinkage.

Since these findings did not allow the selection of a filler, thermal conductivities were derived. The better ability to conduct heat was the reason to optimize mixtures with the product KSM 60/3. Subsequently, this filler was replaced by aggregate. Due to the lower water demand of the aggregate, the amount of solids could be increased while ensuring flowability. These works are represented by the black arrow and the current final recipe is represented by the large green square. This recipe consists of 21.1 wt.-% Portland cement, 15.6 wt.-% limestone filler, 18.9 wt.-% limestone aggregate, 9.4 wt.-% hydrated lime (portlandite), and 35.0 wt.-% tap water.

Fig. 5 shows the solid material properties that are important with regard to the objectives of backfilling measures. Due to the hard criterion of maximum strength and the strong dependence of strength and w/c ratio, the w/c ratios are displayed on the x-axis. The y-axis displays the ratio of limestone (filler + aggregate) to Portland cement. The diagram illustrates even better that the last working steps were carried out with the aim of increasing the thermal conductivity of the material. Currently, the thermal conductivity of the final mixture is about 1.1 W/(m·K), the total porosity 53 vol.-%, and the estimated temperature increase under adiabatic conditions 41 K.

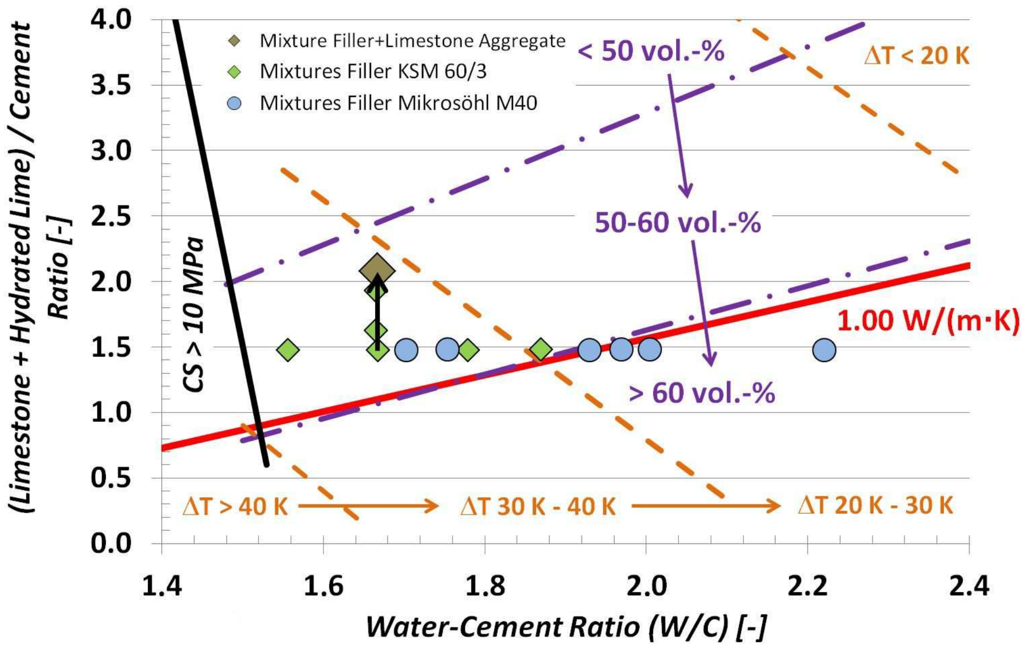

Fig. 5. Ratio (limestone+hydrated lime)/cement and water-cement ratio w/c of conformity field (borderlines) and test mixtures. CS: Compressive strength. Mixtures with w/c ratios of > 2.4 were not investigated because it cannot be ruled out that these mixtures could not harden to a homogeneous solid.

According to these basic rules, backfill materials have been developed for the deep geological facility that is currently being planned by ONDRAF/NIRAS. On the one hand, the results of the investigations show that even small deviations of the requirements can lead to the development of very different backfill materials. However, it also became apparent that it is possible to develop compliant materials within a limited period of time in a simple and efficient way. The information on the conformity fields of the individual material properties are an essential basis for the planning and the performance of the quality assurance during the backfill material production and thus for the demonstration that the goals of the backfilling measures could be implemented successfully.

CONCLUSIONS

Backfilling measures require the production of large quantities of construction materials for longer periods of time. The quantities of building materials often require mixing of the backfill material above ground and then transport over long pipeline lengths. The properties of the backfill material and in particular the production process are therefore influenced to a great extent by variations in the quality of the raw materials. However, the quality requirements for the backfill of deep geological facilities are very high. For this reason, material adjustments must be carried out so that the required material properties are guaranteed at any time. According to the European standard EN 206 [9] backfill materials are to be produced according to properties.

Tasks of DBE TECHNOLOGY GmbH include the derivation of requirements for constructions and building materials that are used in the field of radioactive waste disposal. Compliant materials have been developed, material and safety proves have been carried out, and adequate quality assurance programs are specified. In order to carry out these works systematically and efficiently, working strategies have been developed. They take into account the experience, procedures and methods of classic building material technology, which have to be adapted to the special conditions of radioactive waste disposal.

In addition to the evaluation of state-of-the-art technology, some general principles should be considered during material development:

- When defining test methods and material requirements, the characteristics of the backfilling material and the framework conditions of the backfilling measure must be taken into account. For example, there is no water storage of specimens, because a post-treatment, as in structural engineering is not carried out. Another important topic relate to the functional lifetimes and assessment periods. Their durations are significantly longer than the lifetimes of engineered structures that are stipulated in the technical regulations in force.
- In order to ensure a high quality and conformity with the specifications, it is necessary to define a reference recipe and to have sufficient knowledge about the conformity ranges or fields in dependence of material composition.
- In order to carry out the material development efficiently, simple and quick laboratory tests should first be carried out, followed by first small- and then large-scale studies. In this way, the conformity ranges can be narrowed down quickly.
- The temperature of cement-containing materials increases during hardening and thereafter decreases depending on the amount of hydration heat as well as the extent of heat dissipation. Thermal stresses and shrinkage processes can lead to the formation of cracks and depend on the amount of construction material. The effects must therefore be taken into account in the development of backfill materials. Large-scale experiments, so-called mock-up tests, should thus be an essential part of any material development program.

According to these basics, backfill materials have been developed for the deep geological facility that is currently being planned by ONDRAF/NIRAS. The investigation examples prove that this way, it is possible to obtain backfill materials in a simple and efficient way within a limited period of working time that meet the requirements resulting from disposal of radioactive waste. The general strategy can be adapted to many underground repositories and conventional mines.

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