ROLES OF CLAY AND CONCRETE IN ISOLATING HIGH-LEVEL RADIOACTIVE WASTE IN VERY LONG HOLES

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ABSTRACT
Groundwater flow transports possibly released radionuclides from underground repositories to the biosphere. It can also make construction difficult as is obvious from examining technical solutions for disposal of high-level radioactive waste (HLW) in long subhorizontally bored holes (KBS-3H) and in very deep boreholes (VDH). The presence of intersected, water-bearing fracture zones requires concrete for sealing these parts of the holes while the rest contains canisters surrounded and separated by dense, expandable clay. Casting of the concrete should be preceded by grouting of the fractured rock using cementitious materials composed so that mutual physical and chemical interaction do not degrade either of them. For the sake of rock stability the horizontal holes have to be located at very moderate depth, 400-500 m, where the rock has a high average hydraulic conductivity, while the slimmer, steep holes reaching down to 4 km are kept stable by using clay mud in the construction phase and dense clay for long term performance. The rock at this depth is much less permeable than higher up and the groundwater sufficiently salt to be maintained there, causing only local thermally induced circulation of possibly contaminated water. The KBS-3H concept involves practical difficulties and risks in the installation of the clay seals and waste canisters, for which the risk of shearing by slip of frequently intersected steep fractures is a major threat after closure of the repository. The VDH concept relies on effective sealing of the upper part of the deep holes and puts less demand on the seals in the lower, waste-bearing part, for which the buoyancy conditions of the groundwater make it a major barrier to upward migration of possibly released radionuclides.

Keywords:*Canisters, deep boreholes, Concrete, Groundwater, Grout, Horizontal boreholes, Highlyradioactive waste, Supercontainers, Waste disposal*

1. INTRODUCTION

In addition to the presently favoured repository concept KBS-3V [1] for high-level radioactive waste (HLW), (Figure 1), alternative concepts are being considered by various organizations responsible for disposal of such waste, like the Swedish Nuclear Fuel and Waste Management AB (SKB). Some of them are illustrated in Figure 2 of which the two termed A (VDH) and B (KBS-3H) are presently in focus. The first implies placement of waste canisters in steep, very deep holes reaching down to 4000 m and the second in subhorizontal large-diameter holes at 400-500 m depth. In both cases the waste canisters are embedded in dense smectite clay and installed interchangeably with concrete cast where the holes intersect water-bearing fracture zones [2,3]. For VDH, cement is a small but essential component of the concrete cast where the holes intersect water-bearing fracture zones. Long-term function requires chemical stability, low compressibility and moderate permeability, implying that the cement content is low and the density high.

The concepts have been discussed and assessed in several studies [2,3] concerning the evolution and function of the engineered barriers of clay and concrete and their mutual interaction. Here, we will compare the two concepts with respect to constructability and function.

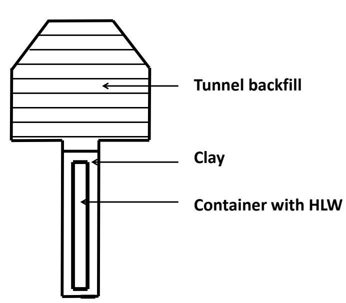

Figure 1. SKB's concept KBS-3V for disposal of highly radioactive waste at about 400 m depth using containers (canisters) surrounded by clay ("buffer") blocks of compacted clay granules. Stacks of annular blocks are placed first and the canisters (containers) are then inserted [1,4].

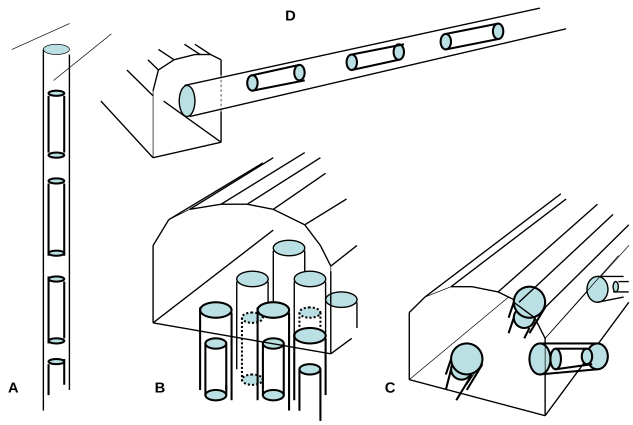

Figure 2.Four alternative HLW disposal concepts for crystalline rock. A) represents VDH and B) KBS-3H. Small cylinders in bigger ones represent canisters surrounded by dense clay [5].

2. PRINCIPLES OF HLW DISPOSAL IN LONG HOLES

2.1 Preparation of the holes, grouting

Fracture zones intersected by the holes may have to be stabilized by grouting. Injection of fine cementitious material can be made by using "megapacker" technique in both steep and subhorizontal holes [6]. Comprehensive research and development has been performed for finding cement-based grouts with optimal properties respecting strength growth, hydraulic conductivity and chemical stability. Grouts based on talc and low-pH cement, which ultimately have high strength, are primary candidates [7]. They are all low-viscous and composed according to modern packing theories that give low porosity and thereby a minimum amount of cement paste. Talc is used as inorganic superplasticizer and reacts with Portland cement to give quick hardening, and with low-pH cement to provide significant strength after a few days. Injection of grouts with densities ranging from 1384 kg/m^3 to 1711 kg/m^3 by use of "dynamic technique" is being tested. The compressive strength of the primary candidate grout is about 20 kPa after 6 hours and 140 kPa after 30 hours.
The hydraulic conductivity is lower than E-9 m/s, which is on the same order of magnitude as that of many fracture zones. The large-scale hydrological performance of the host rock will therefore remain the same as if there were no repository.

2.2 Waste containment

HLW in the form of spent fuel is planned to be encapsulated in metal canisters of copper, iron or titanium and isolated from the rock by use of dense smectite clay. In VDH and KBS-3H the function of the clay is to prevent axial flow of water in the holes and to establish such a tight contact with the rock that no leakage takes place along it. This is achieved by the high swelling pressure exerted by the clay. The concrete seals serve to support the clay, hindering axial displacement, and to prevent clay particles from leaving the clay seals and migrating into fractured rock. The dense clay blocks are fitted in perforated copper tubes that are inserted in the mud-filled holes and moves out through the perforation to form a very dense embedment of the tubes. The concrete seals are cast directly in the holes under water for VDH and within forms for KBS-3H. Long-term performance is required, which makes it necessary to assess the physical and chemical longevity of the seals.

2.2.1 Clay

The clay, termed "buffer",shall be rich in smectite minerals. Such materials have a hydraulic conductivity of about E-10 m/s for a density at water saturation of 1600 kg/m^3, E-11 m/s for 1800 kg/m^3, and E-12 m/s for 1950 kg/m^3 [1,5]. The latter should be aimed at in practice since the expandability, manifested by the swelling pressure, is high, i.e. up to 100 kPa for the lowest density, 300-700 kPa for the intermediate density, and 3-5MPa for the highest. In high-density clay transport of dissolved species and water takes place predominantly by diffusion, while in softer clay it is dominated by flow. The porewater salinity largely controls the bulk conductivity because the softest parts of the microstructural network coagulate in salt water causing widening and increased interconnectivity of the voids [4,5]. A most important fact that manifests the sealing potential of the clay components is that their hydraulic conductivity is lower than that of the surrounding rock for bulk densities exceeding about 1600 kg/m^3 [8].

Chemical processes in the clay embedding canisters and in the sealing zone involve transport of ions that is controlled both by the rate of water flow in the fractures in the surrounding rock and by the rate of ion diffusion inthe rock crystal matrix surrounding the holes, and in the clay.
The models of mineralogical changes in montmorillonite proposed by Grindrod and Takase, Pytte and others [9] consider dissolution and precipitation of phyllosilicates and silicious matter and define the rate of reaction as:

$$r = Ae^{\left(-E_a/_{RT}\right)(K^+)S^2} \quad (1)$$

where: A=coefficient, Ea=activation energy for the conversion of montmorillonite to illite (S to I), R=universal gas constant, T=absolute temperature, K+=potassium concentration in the porewater, and S=specific surface area for reaction.
Experiments by Herbert and others [10] have indicated that the activation energy for the conversion of montmorilloniteis a specific parameter for montmorillonite and related tothe geological origin (especially the temperature during formation of montmorillonite) and the chemical composition of the interlamellar space and the octahedral and tetrahedral layers.The direction of conversion, illitization or smectitization, is driven by dissolution of Si from the montmorillonite and its migration away from location of dissolution under prevailing conditions (dynamic or closed reaction system). Illitization occurs in dynamic reaction system while smectitization appears to be linked to cementation by Si-precipitation, particularly closed reaction systems.
A further aspect is the possible catalytic effect of clay minerals on the corrosion of different metals. Fe-rich dioctahedral smectites appear to accelerate the corrosion of Fe-canisters [11],while those of Cu has shown increasing corrosion under high alkaline pH-conditions (> 9) performed e.g. by bentonite MX-80 [12].
Applying such models the rate of conversion of the smectite species montmorillonite to illite via mixed-layer hybrids has been estimated and found to lead to only 10 % degradation in 100 000 years at 100^{o}C, while it can be 50 % in 100 years at 150^{o}C. This makes a considerable difference between the VDH concept with heating up to 150^{o}C for up to 50-100 years and up to 100^{o}C in the same period for KBS-3H. For VDH the maximum clay and concrete temperature then drops to about 90^{o}C and for KBS-3H to 60oC in a few hundred years [13].

2.2.2 Concrete

A major criterion is that concrete cast for supporting waste containers and fillings in repositories must retain its mechanical strength in the construction phase and serve sufficiently well with respect to hydraulic conductivity and coherence. Concrete with even low content of Portland cement will produce a high-pH plume (pH up to 12) that will affect contacting smectite clay. This effect was quantified in a 3-year borehole sealing experiment in rock and has called for finding less aggressive material with inorganic superplasticizer instead of the organic ones, which can carry possibly released radionuclides into the permeable fracture zone and further to the biosphere [14]. Such work has led to a new type of concrete with talc as superplasticizer and low-pH cement as binder [15]. The aggregate, which consists of ground and milled quartzite mixed with fine quartz, has a grain size ranging from 0.04 to 4 mm, 50 % passing the 0.4 mm sieve.
Table 1 shows the composition of two concretes of potential use, one with low-pH cement (Merit 5000, SSAB Merox AB, Oxelösund) and one with ordinary Portland (Cementa AB, Heidelberg cement group, Sweden) cement. Table 2 shows the time-dependent growth of the uniaxial compressive strength. The maturation of the low-pH concrete is slower than for Portland concrete but the exponential rate of strengthening is 3 times higher after 28 days. Figure 3 shows a typical scanning micrograph of the low-pH concrete indicating tight positioning of aggregate particles and fibrous cement connecting them.

Table 1. Talc (T) concrete recipes. Weight percentages of solids

Cement, %	Talc, %	Aggregate, %	Water/cement ratio	Aggregate/cement ratio	Density, kg/m^3	pH
Merit, 6.5	9.5	84.0	3.6	12.8	2125	10
Portland, 5.2	11.5	83.3	4.5	16.0	2140	13

Table 2.Compressive strength of Portland and Merit 5000 concretes.

Curing time (days)	Compressive strength (MPa)	
	Concrete based on Portland cement and talc	Concrete based on low-pH (Merit 5000) cement and talc
2	0.55	0.01
7	0.66	0.11
28	0.82	2.63

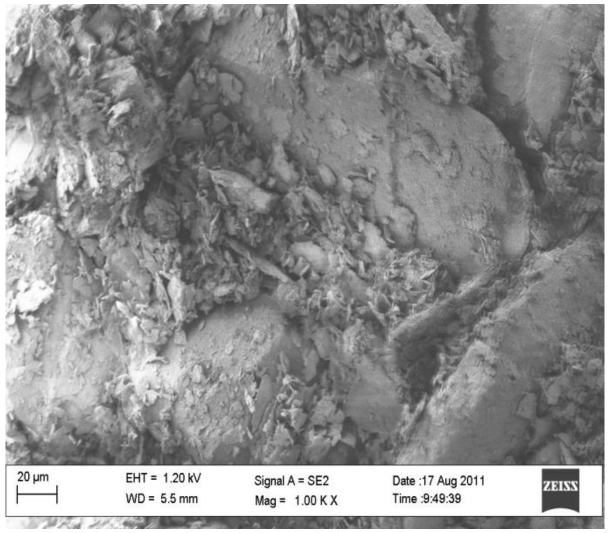

Figure 3.Electron scanning micrograph of concrete with quartzite/quartz aggregate and Merit 5000 low-pH cement. The very high density, about 2300 kg/m^3, gives a low porosity and excellent coherence (Micrographs by Warr, Greifswald University, Germany).

The chemical stability of the concretes considered here is of fundamental importance for their performance in hot parts of the repositories. Hydrothermal treatment of concrete with quartz-rich aggregate, talc and low-pH cement, simulating the conditions in the most heated part of a VDH, causes a manifold increase in compressive strength as indicated in Table 3 [16].This study indicates that strengthening increases with time up to 150oC and that the concrete of this type has a potential to persist in deeply located repositories.

Table 3. Uniaxial compressive strength results of 73 day hydrothermal treatment of talc-concrete with low-pH cement at 73 days age [16].

Sample of Talc-concrete treated at	Compressive strength (MPa)
Room temperature 20 ^oC	4.52
Heating up to 75 ^oC	9.16
Heating up to 150 ^oC	9.00

2.3 General features of long-hole disposal of HLW

The major features of the VDH and KBS-3H concepts are indicated in Figure 4 [2,3]. The intermittent placement of pure clay seals and copper-shielded HLW canisters with 12 BWR elements of spent fuel is needed for avoiding criticality. For VDH the number is 4 [17] and the corresponding threat insignificant. The handling and placement of the canisters requires remote handling, but in contrast to KBS-3V, the VDH and KBS-3H concepts imply simpler and safer disposal of clay-embedded canisters in perforated “supercontainers”. The containers have waste canisters from 2-4 km depth in the 0.8 m diameter VDH (2-4 km), but only clay down to 2 km depth. For KBS-3H, with 1.95 m diameter, larger containers of similar type are installed.

The self-sealingfunction of the clay embedment of the canisters in the perforate supercontainers is illustrated by Figure 5.

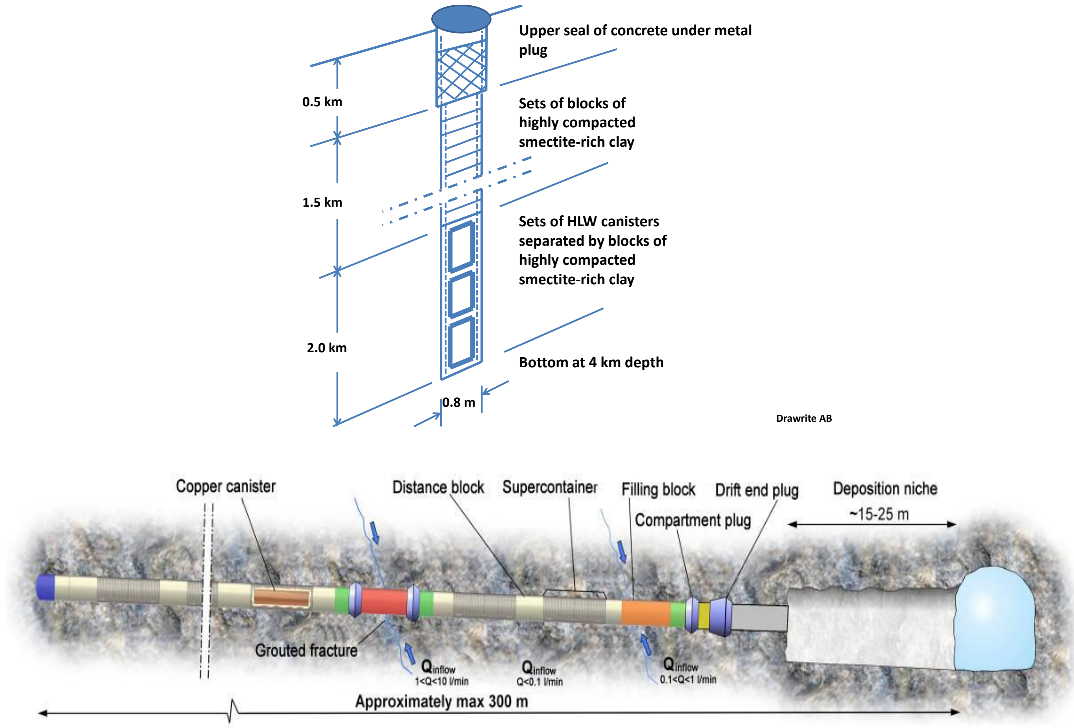

Figure 4.The two long-hole concepts. Upper: VDH with 0.8 m diameter and clay blocks to 2 km depth over the 2-4 km "deployment zone" with HLW supercontainers. Lower: SKB's concept with HLW canisters in 1.95 m diameter subhorizontal holes.

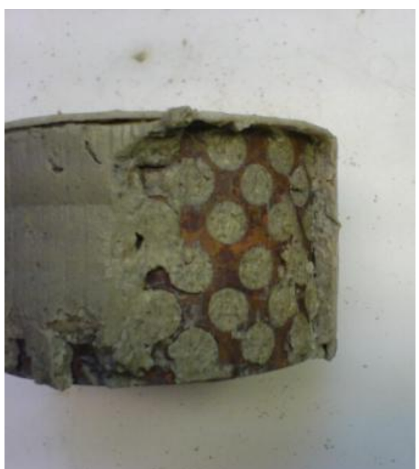

Figure 5.Smectite-rich clay with dry density 1675 kg/m^3 expanded through a perforated "supercontainer" causing consolidating a clay mud after 24 hours. The dry density of the partly removed mud had increased from 160 to 320 kg/m^3[4].

3. DESCRIPTION OF SEALS IN VDH

3.1. General features

Several steep holes with 4 km depth will be bored in slightly different directions from a chamber at a depth of some tens of meters below the ground surface. The distance between their waste-bearing parts will be sufficiently large – a few hundred meters - for avoiding interference and superposition of the individual temperature fields, but sufficiently small to use a common space for establishment of the boring site [17,18,19].

A recently proposed VDH version, illustrated by Figure 6,is referred to in this paper and compared to the long-hole concept KBS-3H. The deep hole is 0.8 m in diameter and the outer diameter of the supercontainers0.70 m. The

HLW canisters are 0.5 m in diameter and contain 4 BWR elements of spent reactor fuel[17]. All supercontainers rest on previously inserted ones except where fracture zones are intersected. Here, concrete is cast up to the upper boundary of the fracture zone. The next sets of supercontainers are inserted when the concrete has matured to get the required bearing capacity. Above 2 km depth, i.e. in the sealed zone, the supercontainers contain only compacted clay blocks.

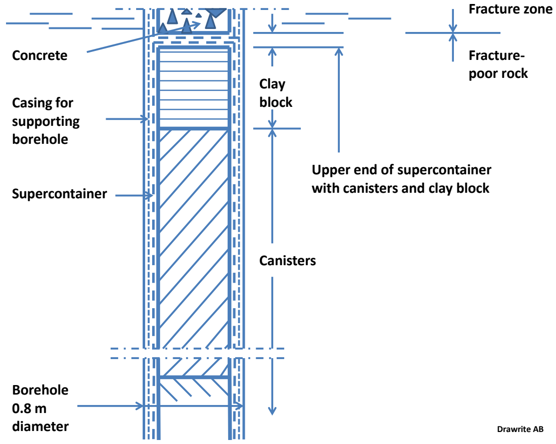

Figure 6.Supercontainer with 0.7 m diameter canister and one clay block in the deployment zone of a VDH. In the "sealed zone" there are no waste canisters. The container submerged in smectite mud and covered by a concrete seal, cast on site.

The bored hole must be stable in the preparation and waste placement phases, which is deemed feasible by various investigators [17,18]. Assuming, for the performance of common type rock mechanical calculations, the same stresses as in the 6 kmdeep German KTB hole [20] and a rock-supporting smectite-rich deployment mud with 1400-1600 kg/m3 density, the VDH is stable and installation of supercontainers possible. An extra stabilizing feature is the installation of a coarse casing of Cu-rich Navy Bronze in the entire hole indicated in Figure 6. It is chemically compatible with the supercontainers and canisters and shall be installed prior to the insertion of supercontainers. Where fracture zones are intersected reaming and stabilization is made parallel to the boring in the way indicated in Figure 7.

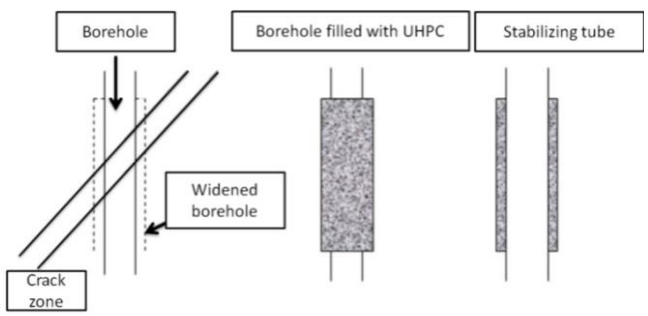

Figure 7.Technique for stabilizing boreholes. Left: Borehole intersecting a fracture zone, Center: Reamed hole filled with concrete between packers, Right: Re-boring gives a stabilized hole [7].

The preparation of the supercontainers with canisters will have to be made by use of robot technique. The containers are kept in radiation-shielded transport tubes until they are lowered into the holes where they sink in the soft mud down to the intended depth. Remote handling is required for transporting and placing the relatively small supercontainers, weighing approximately 6 tons. Big drill rigs with sufficient capacity to lift and tools for handling them are required for placement of casings, supercontainers and construction materials. Preparation and processing of muds and related quality control are made using techniques and criteria worked out in the oil- and gas industry. The establishment of the waste placement site a few tens of meters below the ground surface offers suitable conditions and temperatures for all operative phases.

4. PERFORMANCE OF SEALS IN VDH

4.1. Conditions

In the upper "sealed zone" down to 2 km depth the maximum temperature to which clay and concrete seals will be exposed is estimated at about 100oC for the first one hundred years and to be up to 150oC in the "deployment zone" extending to 4 km depth [17]. The total content of dissolved salt in the groundwater is about 100000 ppm at 2-4 km depth and the density so high that convective flow generated by the heat production will not bring possibly contaminated water higher up than about 70 m above the waste-containing part [6,17]. The Ca/Na ratio is expected to be at least 2 deeper than 2 km, while it is estimated to be 1.5 higher up [13].

4.2. Clay-based components

4.2.1. Mud

The bore mud will serve also as deployment mud. Its main purpose is to support the rock and bring up the rock fragments in the boring phase and thereafter to support the rock. It will undergo consolidation under the pressure exerted by the expanding dense clay in the supercontainers and thereby provide effective sealing. For making it possible to insert the containers the viscosity and bearing capacity of the mud, which should have a density of up to about 1600 kg/m3 [13] must not be too high. They are low when the hot canisters are being installed but rise in conjunction with the consolidation of the mud, aided by stiffening dissolution/precipitation mechanisms after placement when the temperature rises to the predicted temperature of up to 150oC [17,21]. The viscosity may be high enough to require application of a force on the drill string used for bringing the supercontainers down. A number of technical means and know-how are available from oil- and gas prospection and exploitation for the detailed planning and conduction of the work.

A practically important fact is that the clay blocks in the supercontainers start expanding already at the start of placement and initiate consolidation of the surrounding mud, thereby increasing the resistance to bringing the canisters down. It is therefore essential to retard the hydration, which can be made by coating the blocks with a mixture of smectite clay and talc [22]. The coating is assimilated by the expanding clay after about one half day when the container is supposed to be on site. Hydration of the clay blocks in the supercontainers takes place under low to moderate water pressure in the upper parts of a VDH, meaning that a block of 1 m3 size will require thousands of years to become fully water saturated. However, under the very high water pressure that prevails in the deployment zone, water will penetrate the dense, initially unsaturated clay blocks and cause much quicker saturation [23].

The consolidation of the mud makes it a tight seal very early and the wall friction will be high enough already in a few days to carry the supercontainers. The uppermost of the subsequently placed supercontainers shall reach up to a few meters below the next fracture zone where concrete is pumped down through a tube to the upper level of the zone, displacing the mud and filling the hole. Since the clay at the upper end of the latest placed supercontainer becomes stiff in a few days the cast concrete will not penetrate downwards along it [14].

4.2.2. Dense clay

The dense clay in VDH consists of the material that has migrated out through perforation of the supercontainers and of the consolidated mud surrounding them (Figure 5). An ultimate density of at least 1950 kg/m3 of the water saturated matured clay in and around the supercontaineris aimed at. The hydraulic conductivity and swelling pressure of such clay, represented by the commercially available MX-80 bentonite, saturated with low-electrolyte water are known to be E-13 to E-12 m/s, and 3-5 MPa, respectively (cf. Section 2.2.1).

The very high salt content will increase the hydraulic conductivity by 5-10 times and reduce the swelling pressure and expandability by about 50 % [4,6]. For the VDH concept there are two smectitic clay candidates, montmorillonite-rich clay and saponitic clay, i.e. the Mg-equivalent, which is claimed to be more chemically stable [4]. Montmorillonite-rich clay saturated with or exposed to concentrated NaCl solutions at 110oC is known to undergo slight mineralogical changes in the form of partial to complete collapse of montmorillonite stacks, conversion to beidellite, and possible neoformation of sodium illite (brammalite),[24,25]. Microstructural reorganization to give larger aggregates than in untreated clay has been proven. The mechanical stability of the aggregates has been explained to be due to cementation by precipitation of silicious matter that was set free by dissolution of the smectite component.

Applying the models of mineralogical changes in montmorillonite one finds that the same mineralogical processes, causing minor to moderate loss of smectite, will take place in the entire VDH but the rate of conversion to illite and stiffening will be much higher in the temperature interval 100-150oC in the deployment zone. The models imply that an increase in clay temperature from 100 to 150oC speeds up the rate of converting half of the entire original content of montmorillonite to illite by about 100 times [9]. This significant loss of sealing potential will take place in about 100 years but the isolating potential, primarily the hydraulic conductivity will still be considerable. Thus, for pure illite with a density as low as 1600 kg/m3 the hydraulic conductivity is lower than E-8 m/s [7].

4.3. Concrete

Casting of the concrete seals described in Section 2.2.2 requires that it is pumped out from large nozzles extending from a central tube so that the lighter mud is evenly displaced upwards. Occasional mixing of clay and concrete is acceptable. The pH of the concrete, about 10, will not significantly affect contacting clay seals.

The physical stability will be sufficient to allow placement of supercontainers within 2-10 days after casting without risk of movements as concluded from calculation of the vertical pressure caused by the own weight of the successively placed seals, considering also the swelling pressure of the dense clay [26].

5. DESCRIPTION OF SEALS IN KBS-3H

5.1. Clay-based components

5.1.1. Mud

After installation of the supercontainers the gap between the container can be left open or be mud-filled. In the firstmentioned case water dripping from the roof and flowing on the floor will cause non-uniform wetting of the dense clay and volumes of entrapped air that can cause blow-outs. Filling the gap with mud with a density of 1200-1400 kg/m3 is thence recommended (Figure 8). It is thixotropic and flows easily when injected but stiffens quickly after placement.

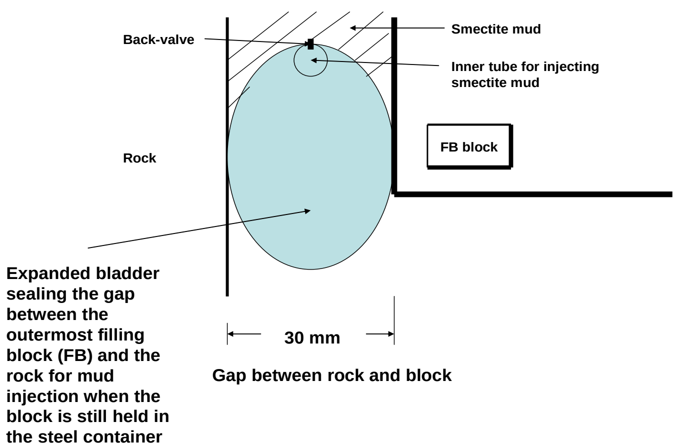

Figure 8. Bladder for isolating the gap to be filled with injected clay mud while keeping the outermost block centered in the drift. The bladder is removed after one day and the placement of more blocks is then continued. FB denotes "Filling Block" in Figure 4.

5.1.2. Dense clay

The supercontainers with clay seals, for which a minimum ultimate density at water saturation of at least 1950 kg/m3 is aimed at, are placed by use of pneumatic techniques. The supercontainers with canisters and clay blocks surrounding them have to be moved in and placed remotely causing considerable risk of being stuck. Injection of mud in the gap between rock and supercontainer can be made after placing one or several units depending on the rate of inflow of water from the rock. As for VDH the major role of the mud is to provide the dense clay with water but unlike this concept the thicker clay embedment of the canisters and the low groundwater pressure cause slower hydration and expansion. Complete water saturation and effective dissipation of heat to the rock may require several decades and even centuries if the repository is located in tight rock.

5.2. Concrete

Intersected steep fracture zones need to be separated from the waste-bearing parts of KBS-3H tunnels or sealed by injecting grout as for VDH. The difference between the two cases is that the hydraulic gradients are higher in the shallow KBS-3H rock, which has made planners propose construction of heavy steel bulkheads for confining the fracture zones and fill the space between them with frictional material. We agree with this principle but assume here that concrete of the talc/low-pH type described in this report is used both for the bulkheads and for filling the space between them.

6. PERFORMANCE OF SEALS IN KBS-3H

6.1. Conditions

The relatively shallow location of a KBS-3H repository implies that the maximum temperature of the clay in the supercontainers can be kept below about 100oC, which hence reduces the degradation of the smectite clay to the same low degree as in the sealing zone of a VDH. In contrast to the latter a significant temperature gradient prevails radially across the clay seals, which causes more comprehensive changes of the clay. The lower salt content of the groundwater in the KBS-3H repository than at depth in VDH is advantageous, however.

The orientation of the long holes means that the statistical probability of dominant steep orientation of fracture zones makes the function of concrete seals more important for the performance of KBS-3H than for VDH.

6.2. Clay seals

6.2.1. Mud

As in a VDH the mud will undergo consolidation under the pressure exerted by the expanding dense clay in the supercontainers. Its density should be up to about 1600 kg/m3 and combine with the dense clay to give early tightening.

6.2.2. Dense clay

A practically important fact is that the clay blocks in the supercontainers start expanding as soon as the mud has been pumped in the gap surrounding them but further hydration of them akes place under low to moderate water pressure, meaning that a block of 1 m^3 size will require thousands of years to become fully water saturated. An ultimate density of at least 1950 kg/m^3 of the water saturated matured clay in and around the supercontaineris aimed at. The hydraulic conductivity and swelling pressure of such clay, represented by the commercially available MX-80 bentonite, saturated with low-electrolyte water are known to be E-12 m/s, and 3-5 MPa, respectively (cf. Section 2.2.1). In contrast to VDH the moderate salt content of the groundwater will not appreciably change the amount of smectite minerals. However, the physical properties can change substantially in the short period of heating to 100oC if the repository is located in very tight rock. Thus, prolonged desiccation and loss of porewater can cause permanent fissures in which salt like gypsum and sodium chloride can accumulate, and precipitation of silicious matter and iron compounds can cause cementation and loss of expandability and self-sealing potential[4].

6.3. Concrete

The temperature in those parts of the KBS-3H where concrete has been cast will not exceed 50-60^{o}C. As indicated in Section 4.2 the strength of the talc concrete samples hydrothermally treated at 75^{o}C were significantly higher than those matured at room temperature, which supports the hypothesis that talc concrete with low-pH cement is chemically very stable in contrast to that of Portland cement [16,27,28,29,30,31]. Although the chemical attack by the very aggressive treatment of the concrete in the accelerated test under chemically open conditions did not cause any dramatic degradation one still has to assume that the cement reaction components will be successively dissolved and lost. Assuming that this is controlled by diffusion it will probably take thousands to tens of thousands of years before the big concrete units consisting of pairs of bulkheads with concrete between them have been transformed to densely packed aggregate material with no cohesion.

7. DISCUSSION AND CONCLUSION

7.1. Role of rock

The structure of the host rock determines the frequency of fracture zones that will be intersected by the long holes, and the access to water for hydration of the dense clay. The steep orientation of VDH implies fewer but longer concrete seals than in a KBS-3H repository. Location of the latter in tight rock will lead to longer hydration time and more obvious risk of degradation of the dense clay than in the “sealed zone” of a VDH. For the clay in the “deployment zone” of a VDH the risk of permanent stiffening and loss of self-sealing capacity is higher, however.

The risk of rock fall or seismically induced deformation is deemed stronger for KBS-3H and for VDH, since the steep holes are currently supported by mud and casings. For KBS-3H one must foresee loosening and fall of wedges from the roof, which would be disastrous in the waste transport and placement phases (Figure 9).

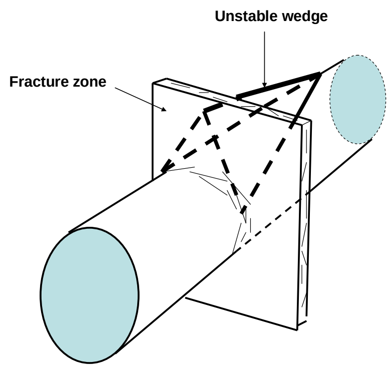

Figure 9. Unstable wedge formed where the tunnel intersects a fracture zone.

7.2. Constructability

No repository of either type has yet been constructed and several of the assumed or proposed techniques have never been tried. However, deep borings with large diameters have been made in Germany and the US and in Russia. The 12 km deep borehole with dimensions like those of the VDH in the Murmansk area is a definite proof that deep drilling is feasible [6].

Placement of supercontainers is deemed simpler and safer in VDH than in KBS-3H since gravity assists in the placement of the smaller canisters of the firstmentioned concept. The mud confining the supercontainers is in the VDH from the start of the waste placement process while it must be injected remotely afterwards in KBS-H.

7.3. Waste isolation capacity

In recent time the isolating capacity of the host rock of repositories has been judged to be very limited and to serve only as a mechanical protection of the waste [32]. This puts a demand on the engineered barriers but for VDH effective waste isolation is achieved also by another factor. Thus, while the basic performance principle of a KBS-3H repository is to rely on canisters that shall be tight for at least 100000 years, the major isolation capacity of a VDH is provided by the differences in groundwater density in the "deployment zone" extending from 3 to 4 km depth. The heavy groundwater in this interval cannot move up to ground surface. The zonation of the groundwater caused by the differences in density is stable as demonstrated by the fact that salt water that has not been in contact with surface-near conditions for millions of years has been found at depths of several kilometers [19,20].

7.4. Retrievability of HLW

Retrievability, which can only be considered rather early after placement of the waste is believed to be possible but very demanding in both concepts. The bigger and heavier supercontainers of KBS-3H offer greater difficulties than VDH.

7.5. Overall assessment

On summing up it is concluded that the advantages of the VDH concept outweigh those of KBS-3H. However, complementary investigations in the form of bench- and intermediate-scale tests over several years are required for verifying the theoretically derived evolution of the mud, clay and concrete and for validating the feasibility of the various construction phases. A couple of available deep boreholes should be used for demonstrating the constructability and waste placement technology.

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