LARGE-SCALE BACKFILLING SIMULATIONS AT ÄSPÖ LABORATORY SWEDEN AND APPLICABILITY OF RESULTS TO REPOSITORY CONCEPTS CONSIDERED FOR CANADA

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ABSTRACT

As part of the Nuclear Waste Management Organisation's (NWMO's) Adaptive Phased Management (APM) approach to development of deep geological repository concepts for the permanent disposal of used nuclear fuel, effort is being put into reviewing, assessing and where possible participating in international activities associated with repository sealing in a variety of geological host media. Of considerable interest are developments related to backfilling and closure of the repository openings following placement of the used fuel containers (UFCs).

In a host medium such as granite, the potential exists for localized inflow of water or combining of small localized inflows into larger features if flow is not managed. Under conditions of high inflow these could form channelled flow features (piping features) through backfilled rooms or tunnels. This could cause erosion of the backfill and complicate ongoing construction and installation activities within the affected room. While UFCs would not be installed in locations where unsuitable hydraulic conditions exist (i.e., high inflow rates), tunnels may pass through such hydraulic features and hence the backfill installed in those locations must be able to deal with the accumulated inflow from these and other smaller features. Posiva and SKB have been examining how water enters and passes through backfill materials at laboratory- to nearly full-scales ($1/12^{th}$ to ½–scale placement room cross-section) in order to define when water inflow begins to become disruptive to the backfill. Additionally, studies to determine the effects of varying the composition of the backfill blocks and pellets on system performance have also been examined as part of the process of design optimization.

Work by SKB and Posiva has demonstrated that backfilling of placement rooms in crystalline rock environments can be achieved using a combination of precompacted clay blocks and clay pellets using modified conventional equipment. There are hydrogeological conditions that could be potentially disruptive to newly placed backfill, in particular the inflow of water to the room and its subsequent movement through the unsaturated backfill. Tests have evaluated a number of backfill materials options, the effects of intersecting fracture features, rate of water influx and how isolated pockets of unsaturated backfill may respond to subsequent water influx.

Keywords: tunnel, backfill, barrier, clay blocks, gaps, pellets, Äspö

1. BACKGROUND

Figure 1 shows NWMO's generic In-Floor Borehole (IFB) concept for use a Deep Geological Repository (DGR) in a crystalline rock environment and the sealing materials associated with it [1]. The NWMO's IFB concept is similar to the KBS-3V concept being evaluated by SKB and Posiva and so technologies developed in those programs have relevance to NWMO. Information and technology developed to facilitate backfill installation in a crystalline rock environment also has applicability to other geologic media. Many of the processes examined are associated with the pre-closure period and so are to a considerable degree medium-insensitive since inflowing water seems to affect the pellet-rock interface, an interface that will be present regardless of the geological medium. The terminology used to describe the components of the backfilling concepts adopted by SKB and Posiva differ from NWMO's terminology (e.g., container = canister; placement room = deposition tunnel) so to maintain consistency, the NWMO terminology is used where-ever possible in this paper. SKB and Posiva also differentiate between placement tunnels and those beyond, hence the materials used in backfilling excavations beyond the placement tunnels may differ but in this paper, discussion is limited to placement room (deposition tunnel) backfilling.

Basic functional specifications associated with the backfill as a whole have been identified by SKB and Posiva [5], these are also relevant to NWMO's repository backfill. Assessment of materials options and generic backfilling approaches followed by determination of how well they met the requirements established for them were described by SKB as follows:

1) Nuclear safety and radiation protection

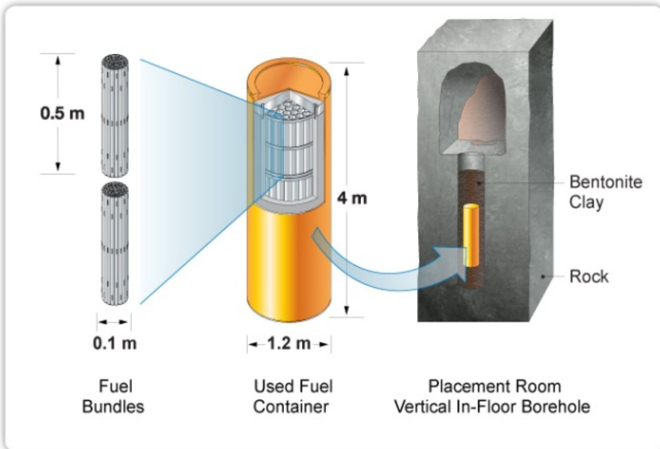
- The backfill shall restrict advective transport in deposition tunnels so that the function of the bedrock is not impaired.
- The backfill in deposition tunnels shall restrict the upwards swelling/expansion of the buffer so that the function of the buffer is not impaired.
- The backfill shall not in other ways significantly impair the safety function of the barriers.
- The backfill shall be long-term resistant and its function shall be preserved in the environment expected in the repository.
- The backfill (manufacturing and emplacement) shall be based on well-tried or tested technique.
- The backfill properties shall be controlled using specified acceptance criteria.

2) Environmental impact

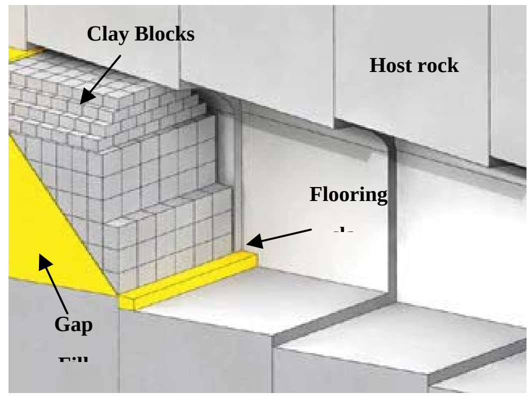
- The manufacturing of the backfill and its emplacement shall be efficient regarding consumption of raw material and energy.

3) Flexibility and efficiency

- It shall be possible to perform the placement of the backfill at the specified rate.
- The backfill shall be cost efficient with respect to raw-materials, manufacturing and emplacement.



(a) NWMO In-floor Borehole (IFB) Concept [1]



(b) Block backfilling showing clay flooring, gap fill and precompacted blocks [2]

Figure 1. In-floor borehole concept for a DGR and block backfilling concept.

Generic concepts for installation of tunnel backfill have been developed and tested by SKB and Posiva and various components that are applicable to backfilling have also been investigated in Canada [3, 4]. The concept showing the most promise for use in the placement rooms associated with the IFB concept is referred to as the block and pellet method. This geometry calls for the following materials to be used as backfilling progresses stepwise along a placement room:

- Clay pellets or crushed clay materials are used to provide a level floor,
- Blocks of precompacted clay (or clay-aggregate composition) are then installed on the flooring materials. These blocks fill the majority of the room volume (>80%).
- The remaining gaps at the walls and roof are then filled with more clay pellets.

In addition to meeting the above-listed, long-term functional goals, materials and placement options need to be developed that provide a high degree of confidence regarding the ability of the backfill to withstand water inflow during, or immediately following its installation. SKB and Posiva's ongoing backfill development program is investigating compositional options for tunnel backfill and methods for its placement with this goal in mind. Work is ongoing at various laboratories in Sweden and Finland and large-scale demonstrations and trials have been completed at SKB's Äspö hard-rock laboratory (HRL) [2, 6, 7, 8, 9] and more are planned. The progress of the ongoing backfill development work and demonstration activities at Äspö has been closely followed as part of NWMO's ongoing interest in joint research activities and international programs. NWMO has provided in-kind contributions in the form of the results obtained from small-scale simulations completed in Canada for NWMO by Atomic Energy of Canada [7], as well as supporting Canadian participation in technical meetings associated with the studies undertaken in Sweden.

2. MOCK-UPS AND LARGE-SCALE BACKFILLING TESTS

2.1 Previous laboratory and large-scale mock-up testing

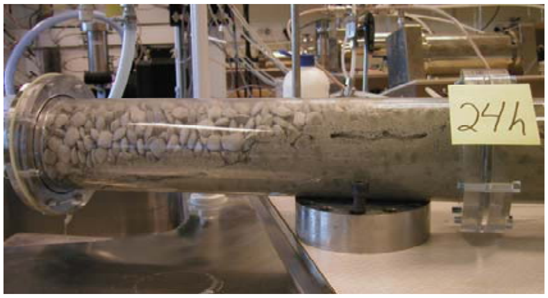
The pellets and blocks must have very low water permeability and an ability to swell as the clay hydrates, closing any gaps or joints remaining after backfill installation. In order to exhibit such behaviour the clay used in the blocks and pellets must contain a substantial swelling clay (smectite) component. The most common swelling clay is montmorillonite, and materials containing high montmorillonite content are commercially marketed under the generic name of bentonite. The backfill component in the IFB concept does not need to exhibit a high swelling pressure (approximately 100-200 kPa (REFS [10, 11] SKB, Posiva), once system saturation is achieved. However, even a modest swelling pressure will still require the presence of a substantial swelling clay component, especially under conditions where saline groundwater is encountered.

Laboratory tests have been completed on pellet materials considered for use as part of deposition room backfilling [13, 14, 15]. Two important properties investigated regarding bentonite pellet when used in the slot between high compacted bentonite blocks and a tunnel wall where the wetting behaviour, i.e., the ability of the pellet filling to store water and the sensitivity for piping and erosion. Other properties investigated were the healing ability after a piping scenario and the homogenization of backfill blocks and bentonite pellets (Figure 2a).

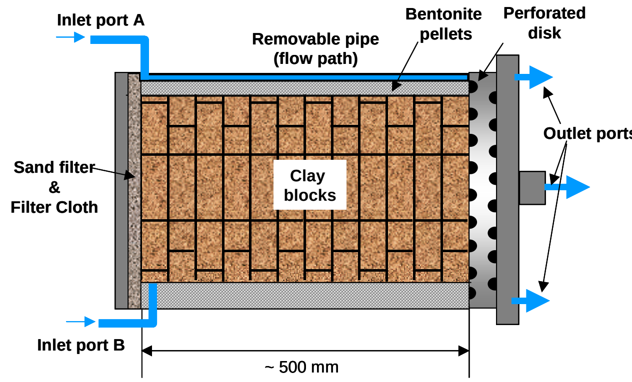
The manner in which water initially moves into and through backfill materials installed in simulated tunnel sections of various scales has been examined discussed and summarized [6, 7, 8, 9, 13, 15, 16, 17, 18, 19]. These studies examined the potential for point sources of water flowing into an unsaturated section of deposition room backfilled with precompacted clay blocks and extruded bentonite pellets to physical disrupt the backfill. The equipment and layouts shown in Figure 2 were used in these examinations.

Inflow rate can affect backfill stability and that system mechanical stability was adversely affected by high point inflows (or combined inflows moving along a single flow path) [6, 7, 8, 9, 19]. Laboratory studies have reported on the effects of groundwater salinity on pellet erosion [13] and water movement through saturated clay-based materials, including those being considered as potential buffer or backfilling components [20, 21, 22]. These tests found that as Total Dissolved Solids (TDS) increased, the saturated hydraulic conductivity increased while swelling pressure decreased for a given material and density. These relationships are of considerable importance to repository application in Canada where groundwater salinities can be very substantial, ~75 g/L in granitic environments and ~270 g/L in some sedimentary environments; although at high density the effect of salinity becomes less pronounced.

Testing by Sandén et al. [13] examined initial water movement into and through pellet materials while others examined how water initially moves into large pellet-block assemblies ($1/12^{th}$ to ½ - tunnel scales) [6, 7, 8, 9, 19, 23]. These tests examined the effects water inflow rate, permeant salinity (Total Dissolved Solids, TDS), clay type and dimensioning have on water uptake and distribution, clay erosion and mechanical stability of unsaturated backfill. Specifically, flow along the sidewall and crown regions were examined, the floor was not included as a source of water in these tests. Other tests have been completed on flooring materials and interaction between pellets and natural rock supplying water via discrete inflow points show results that indicate that flow will tend to occur along the pellet-block interface rather than the rock-pellet interface observed in most of the simulations completed to date. The behaviour of flooring materials supplied with water is described in a report currently being prepared by SKB.



(a) Bench-scale water uptake tests [13]



(b) 1/12-Scale Simulator [7]

(c) ¼- Scale Simulator [19]

½-Scale Simulator Clay Blocks in Place Completed Assembly

(d) [9]

Figure 2. Backfill pellet and pellet-block tests.

Some common trends were observed in all of the larger-scale pellet-block tests, e.g., initial outflow from test assemblies usually occurred at the pellet-chamber contact. Dixon et al. (2008c) identified three different behavioural regimes related to rate of water supply to a pellet-block backfill system percolated using a 1% TDS water. Subsequent testing under higher TDS groundwater conditions and different backfill materials [19], indicate that the boundaries for these three regimes may change depending on test specifications:

1. Where inflow from a single location was in the order of 0.1 L/min, movement of water towards the downstream face of the backfilled volume was slower and more of the inflow was drawn into the pellets and the clay blocks. Outflow from such systems tended to contain essentially no suspended or entrained solids.
2. Where inflow from a single point ranged from ~0.1 to 0.5 L/min, the time for water to begin exiting the backfilled volume decreased with increasing inflow rate. Erosion of backfill could be readily observed with erosion rate increasing with flow rate. The amount of erosion was still relatively low, tending to decrease with time and reducing rate was attributed to development of a stable flow path at the chamber-pellet boundary.
3. For high inflow conditions (point or combined inflows of >0.5 L/min), water penetration to the downstream face occurred very rapidly with little and only localized water uptake by the pellet-block backfill. These systems also experienced considerable erosion of the backfill as the result of the high flow velocities. Where flow along a single channel reached or exceeded 2.5 L/min, water movement to the downstream face of the backfilled volume was rapid, as was onset of substantial and ongoing erosion of the materials closest to the tunnel wall (pellet materials), but eventually the block materials would also be involved.

Additionally, the pellet-block backfill materials have only a limited capacity to act as a temporary sink for inflowing water (delaying of water movement along tunnel) and only very low hydraulic head is needed before channelling of water occurs (typically along the clay-pellet – chamber wall interface).

2.2 Results of recent ½ -scale tests

Recent testing in the 1/2-scale simulator at Äspö have examined the role of geological features on initial water movement through a 4 to 6-m long section of tunnel using the mock-up shown in Figure 2 [9]. The tunnel mock-up was constructed in such a way that a simulated fracture feature intersected the entire perimeter (excepting floor) of the tunnel (Figure 3). Water was supplied to the pellet-block mock-up at the location of the fracture(s) or else at the rear of the chamber and the effects of discrete flow feature encountering a fracture was evaluated.

Figure 4 through Figure 7 show the type of behaviour observed in these simulations. What was immediately obvious was that water entering the system via a fracture feature (Figure 4 and Figure 5), was not discernibly impeded with regards to its subsequent movement towards the open face of the mock-up and that flow typically developed along a single pathway, resulting in limited short-term water uptake. It required only a small hydraulic head in order to induce flow along the pellet-chamber wall contact.

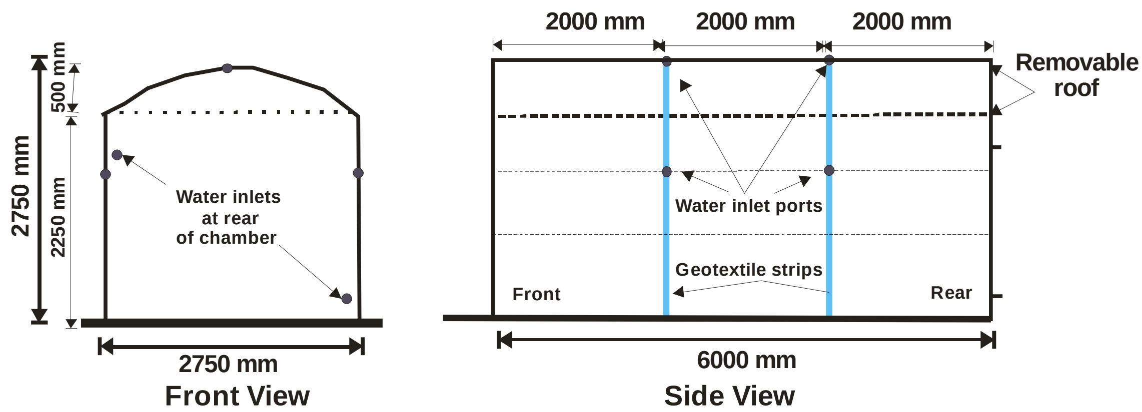


Figure 3. Schematic of ½-scale chamber showing location of water inlet ports used to supply the artificial fracture [9].

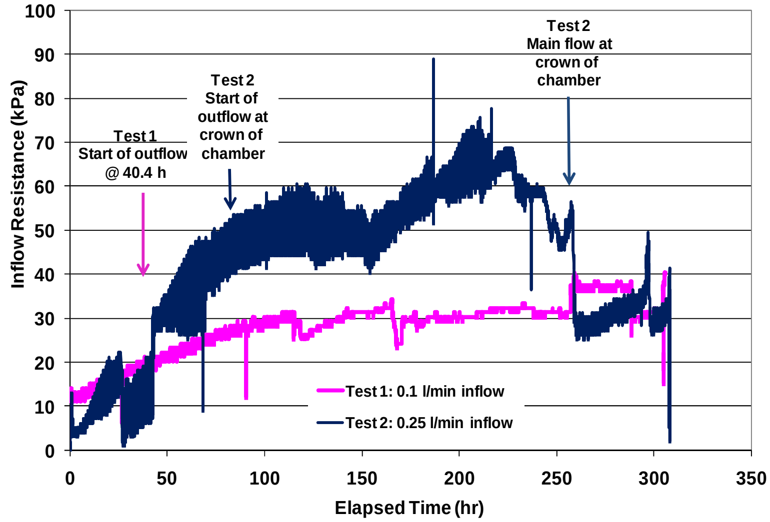
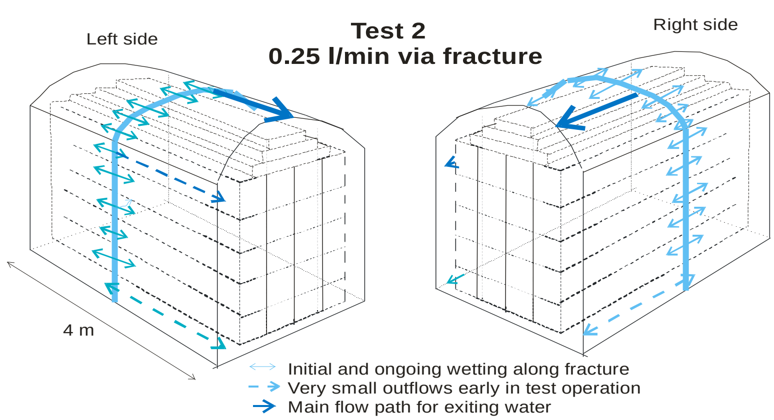


Figure 4. Resistance to water entry into clay via a simulated fracture [9].



Water movement in test where water supplied at 0.25 L/min to a narrow fracture feature

Pellet materials eroded from mock-up

Figure 5. Movement of water supplied by a fracture feature into and past backfill [9].

Figure 6 and Figure 7 illustrate a more complex geometry where water moving from locations beyond the last 6 m of backfilled tunnel intersect fracture features that have been supplying water very slowly to the adjacent pellet fill (forming a localized gasket-like feature between the chamber wall and the clay blocks). Originally separate flow features once again combined but unlike previous tests, a substantial quantity of water was stored in the isolated region, delaying the eventual arrival of water at the downstream face of the mock-up. The air trapped in the isolated region underwent pressurization until it could forcibly breach the gasket (<200 kPa). Water ultimately made its way towards the downstream face of the backfilled tunnel. Ultimately the final gasket-like feature was breached, resulting in the sudden escape of the trapped air and expulsion of air/water into the open tunnel, with formation of a flow path that was able to cause considerable ongoing erosion of the pellet fill.

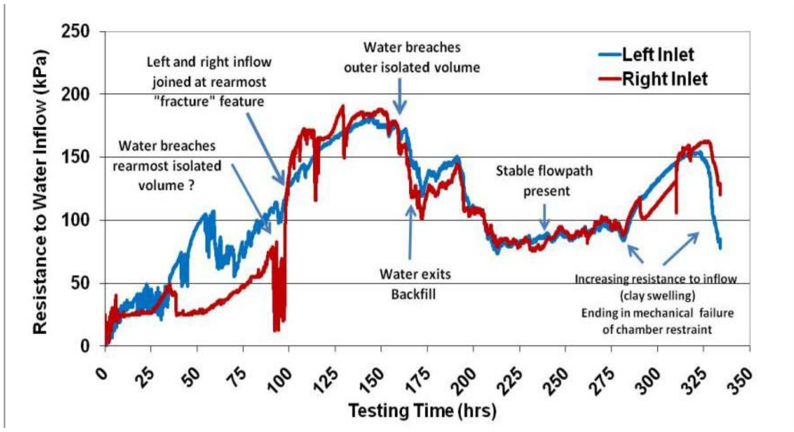
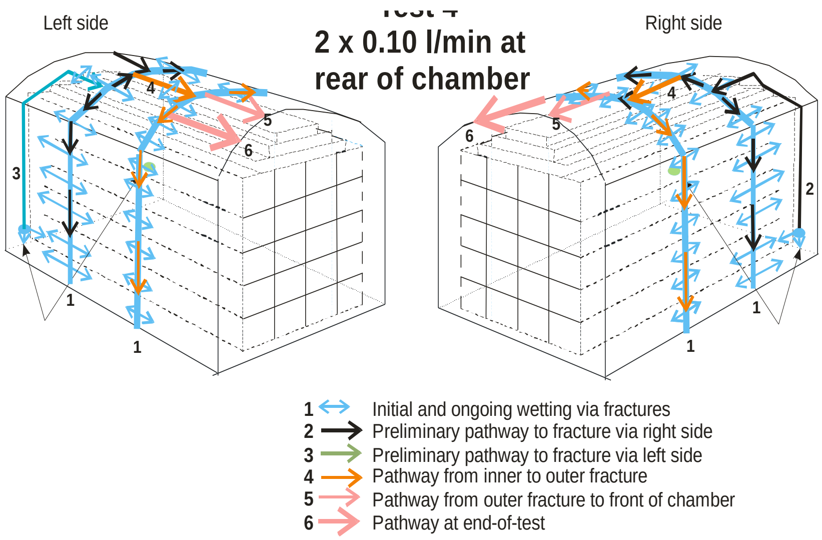


Figure 6. Backfill-induced resistance to two water sources intersecting non-waterbearing fractures (2 x 0.1 L/min water sources) [9].



Water flow past 2 fracture features Clay eroded by exiting water

Figure 7. Water movement into and past a backfilled tunnel where fracture features exist [9].

2.3 Interpretation of large-scale test results

The results of studies related to water entry, uptake and movement through a backfilled mockup of a 6-m-long section of an SKB deposition tunnel has determined that backfill disruption could occur during the period immediately following its installation. Such disturbance would be associated with locations where flow exceeds approximately 0.25 L/m along a single pathway and groundwater salinity is low. The general evolution of such a system can be described as being controlled as follows:

- Initially, water uptake by the pellet fill tends to be heterogeneous and under high water inflow conditions can move rapidly from the inflow point towards an unplugged room entrance.
- It is possible to create a piping feature in a backfilled room under high point inflow rates and erosion may occur.
- Where the volume of pellet fill is limited, water can move into the block-filled volume, potentially generating preferential flow paths along block boundaries.
- In situations where interface flow develops, the feature tends to occur along pre-existing interfaces, especially the pellet-rock boundary. Under low flow (<0.2 L/min) conditions, interface flow does not result in extensive backfill erosion but water will move rapidly towards the downstream face of the backfill.
- Localized seepage from intersecting fractures rather than a single point can substantially affect subsequent saturation of the backfill, rate of water movement along the room and the development of pressurized air pockets within the repository. Such features may have a disruptive effect in the period prior to installation of the mechanical plug at the end of the placement room.
- After plug installation at the end of the placement room or if need be, at an intermediate point within the room, piping, interface flow and trapped air should have limited potential to cause disruption to the backfill.

Where water inflow occurs at very low rates (< ~0.1 L/min), especially if associated with a dispersed source, water uptake by the adjacent pellets will be substantial and water migration to the downstream face will be slowed. Ultimately, even if a discrete flow feature forms, transmitting water to the downstream face, such low flow rates are generally not sufficient to induce discernible physical erosion of the pellet materials.

3. CONCLUSIONS

The tests completed by SKB, Posiva and NWMO all provide valuable information on the likely pattern of water movement will be in a backfilled placement room if there is any substantial inflow of low-salinity water prior to its closure. At low inflow rate (or very dispersed water entry) the distance of the source from the downstream face of an open room will affect the time required for water to reach the open section of room. Water will gradually be absorbed by the clay pellets, providing some delay in the time required for generation of preferential flow pathways (expected to be along the clay-rock interface initially). Once the placement room is closed, the system is less susceptible to disruption by the inflowing water as there will be limited opportunity for solids to be redistributed. The presence of air trapped during room construction may result in the generation of considerable gas pressure in a closed room or isolated section of a room. This should be monitored during the period prior to room closure as venting of the air could be disruptive with respect to the subsequent erosion-resistance of the backfill.

The chemical composition of any substantive water supply to the room in the period prior to its permanent closure needs to be monitored and assessed as part of routine backfilling operations. High TDS contents result in systems that are more vulnerable to erosion by through-flowing water and also have a lower free-swell capacity, lower swelling pressure when saturated and a higher saturated hydraulic conductivity.

The behaviour observed in these and previously completed tests are relevant to any geological host medium that has the potential to experience substantial ongoing water supply to a newly backfilled section of room. For rooms or room sections where there is little-or-no water influx during the period of placement room backfilling, the potential for disruption by water is not present. In such situations parameters like groundwater salinity become less important so long as the long-term behaviour of these materials, once saturation is achieved, meet the performance requirements for backfill.

Surface-based construction trials conducted using the block and pellet concept has demonstrated that backfilling can be accomplished such that the long-term saturated behaviour of backfill meets the goals set for it. There are still issues related to developing means of consistently achieving density targets, especially for the pellet fill but all block and pellet placement trials conducted so far, will develop swelling pressures well in excess of, and hydraulic conductivities far lower than what is currently defined as being necessary for a backfill by SKB and Posiva. Work has also established that a wide range of swelling clay products can meet the currently defined hydraulic and mechanical requirements for backfill.

As the environment at each yet-to-be selected candidate sites for NWMO's DGR is characterized backfilling and sealing designs will be developed. Work to develop and demonstrate backfilling materials and methods that have been undertaken by Posiva, SKB and NWMO will provide a valuable source of background information related to operational planning, backfilling materials and methods options. It will also allow for prediction of short-term system behaviour and anticipated longer evolution of the backfill and closure system.

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