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Abstract

The report describes the outcome of the work within the project **“SU5 08.20 Impact of water inflow in deposition tunnels”. Project decision SKBdoc 1178871 Version 3.0.**

Two activity plans have been used for the field work: AP TD SU50820-09-019 and AP TD SU 50820-09-071.

SKB and Posiva have been examining those processes that may have particularly strong effects on the evolution of a newly backfilled deposition tunnel in a KBS-3V repository. These assessments have involved the conduct of increasingly large and complex laboratory tests and simulations of a backfilled tunnel section. In this series of four tests, the effect of water inflow into a backfilled tunnel section via an intersecting fracture feature was evaluated. The tests included the monitoring of mock-ups where water entered via the simulated fractures as well as evaluation of what the effect of isolated tunnel sections caused by localized water inflow would have on subsequent evolution of these isolated sections.

It was found that even a slowly seeping fracture can have a substantial effect on the backfill evolution as it will cause development of a gasket-like feature that effectively cuts of air and water movement from inner to outer regions of the backfilled tunnel. Water entering via these fractures will ultimately move out of the tunnel via a single discrete flow path, in a manner similar to what was observed in previous ½-scale and smaller simulations. If the low-rate of water inflow from fracture is the only source of water inflow to the tunnel this will result in hydraulic behaviour similar to that observed for a single inflow point in previous tests. The presence of a fracture feature will however result in a larger proportion of water uptake by the process of suction than might occur in a point inflow situation and hence a more uniform water distribution will be present in the pellet fill. This also results in a greater tendency for water to be absorbed into the adjacent block fill material and more rapid initiation of the swelling of this material and subsequent localised compression of the pellet fill.

These fracture features with their gasket-like effect, can have a very substantial effect on the way in which water moves into the backfilled tunnel behind this feature. The generation of an isolated, air-filled pocket behind the gasket is not immediately problematic but when water begins to enter this isolated volume, the result is development of a pressurized pocket within the tunnel. Ultimately this pocket will/may rupture the swelled clay gasket associated with the fracture feature and release pressurized air/water into the region downstream of the fracture. This process is likely to be encountered as backfilling progresses and may occur several times over the course of tunnel saturation (in the period before the deposition tunnel plug is installed) and could result in locally high erosion rates and disruption of the backfilling operations at the downstream face of the backfilled tunnel volume.

Summary

The ½-scale tests described in this report were done at SKB's Bentonite Laboratory at Äspö and were focussed on the short-term behaviour of the backfill (1-day to 2 weeks) following its installation and has provided further insight into the early evolution of the deposition tunnel backfill.

The results from the current test series have highlighted the critical influence of water inflow rate and pattern on subsequent discharge from the downstream face of an incompletely backfilled tunnel. In particular, the presence of a clay having a higher smectite content (Milos B versus Friedland) resulted in a somewhat tighter contact being developed at the backfill-chamber interface. This had only limited effect on the subsequent movement of water through the backfill when inflow as outflow occurred from the same region of the tunnel in the majority of the tests completed (excepting where there was exceptionally high point inflow rate).

Where pockets of dry backfill were isolated by zones of nearly-saturated clay by the action of localized seepage from an intersecting fracture, behaviour was notable different than had previously been observed. Under such conditions, the backfill was able to contain much more inflowing water before water was able to force its way along the chamber-pellet boundary to the downstream face of the backfill. This situation provides for more time between pellet installation and water exit from the backfill, but when water does breach the saturated regions, it does so very energetically and subsequently results in an elevated rate of pellet erosion. The presence of the simulated fracture feature also served to allow previously independant, essentially non-erosive flow features to link and cause substantial erosion to the pellet-fill. Means to deal with combined flow features and compressed air within the tunnel will need to be established in order to reduce the risk of disrupting ongoing backfilling operations or compromising the already backfilled volume. This could be examined through further trials in the ½-scale simulator where technical solutions could be tested in a controlled environment before larger, more complex and less well controlled demonstrations are conducted in an underground environment.

The installation and subsequent saturation of Milos B or a high density Friedland clay – Cebogel deposition tunnel backfills of the type proposed by SKB will ultimately apply substantial swelling pressure on the walls of the tunnel and will over the longer-term (post saturation and EMDD equilibration) will exert >800 kPa (800–4,080 kPa) of pressure on the tunnel walls under low salinity conditions. Low salinity would include TDS conditions (<1%). Under more saline conditions (>3.5% TDS), the effects of TDS on swelling pressures will be notable but would still, even using conservative assumptions be in excess of 480 kPa for Milo B and 840 kPa for Friedland backfills. Even with such a reduction in the equilibrated swelling pressure, the swelling pressure for the backfills examined far exceed the 200 kPa target set by Posiva.

At high TDS during the initial stages of water uptake, the pellet fill is of low density and compression by the internal block fill has not occurred. Under such conditions there will be limited swelling capacity and hence a reduced resistance to the movement of water through and erosion of the pellet fill.

The tests described in this report show that there is some delay in water movement through the backfill and the time is dependant on a number of factors including:

- Rate of water inflow to the tunnel.
- Pattern of water inflow (point source or dispersed water seepage).
- The presence of intersecting geological features, (fractures).
- Distance of water source from front face of backfill.
- Phase of backfilling operations (early where there is only a short tunnel length filled or later where large volume is filled and multiple small inflow points could potentially combine into a single large flow feature.

Other factors such isolation and subsequent pressurization of air within the tunnels will also affect water movement, uptake and subsequent erosion of the pellet-filled portions of the backfill.

For a dry tunnel sections with few inlet sources, a first estimate of the average rate of water penetration along the chamber wall – pellet interface caused by a limited number of inflow features (1 or 2) is approximately 1–1.5 m per day under a total inflow rate of ~ 0.2–0.25 l/min inflow. Higher inflow rates are likely to result in higher rates of penetration, as will disruptive de-gassing events. This rate of water penetration is approximately one half that observed in previous tests where water was supplied to the tests at a single point and there were no features causing resistance to water movement (e.g. wet regions downstream of main water source or intersecting fracture features). This would seem to indicate that in a relatively dry tunnel section at a backfill installation rate of 5–6 m/day that there would be approximately 2 to 5 days before water could move the distance that would be backfilled in a single day. It should be stressed that this is only a crude estimate and numerous factors will affect what occurs in the field.

There is still the need to compile and assess the results of 1/12th scale tests done at the Äspö facility with the ¼-scale tests completed in Finland with regards to materials, boundary conditions and backfill susceptibility to erosion. Once this is done it will be possible to compare these data to the results of the ½-scale tests completed at SKB's Bentonite Laboratory at Äspö to determine if there are any as-yet unidentified scale-related differences in backfill behaviour. At that time it may be useful to conduct additional ½-scale tests.

Ultimately, there will be a need to complete full-scale backfilling demonstrations in an underground environment where the rock and hydraulic environment is comparable to what will be encountered in a repository. The tests described in this report have provided valuable supporting information that will assist in planning such underground demonstration of technology and materials as well as identifying what technical issues may require further assessment for an operating repository.

Sammanfattning

De ½-skala tester som beskrivs i denna rapport genomfördes vid SKB:s Bentonit Laboratorium på Äspö och fokuserade på det inledande skedet om hur vatten tas upp och fördelas i den återfyllda tunneln under de första 1–2 dygnen.

Resultatet från den genomförda testserien belyser det kritiska inflödet, samt fördelningen fram mot den öppna fronten på en icke återfylld tunnel. Speciell jämförelse mellan leror med hög svällnings kapacitet (MilosB/Friedland) resulterade i en något tätare kontakt mellan återfyllnaden och stålväggen i testkammaren. Detta medförde endast begränsad effekt på genomströmningen i återfyllnaden när inflöde och utflöde kom från samma område i uppställningen i de flesta av testuppställningarna (förutom där det var ett exceptionellt punktinflöde).

Där ”torra fickor” bildades omgärdade av delvis fuktad lera från lokalt inflöde, noterades en ny erfarenhet som inte visat sig vid tidigare experiment. Under dessa förhållanden kunde återfyllningen ta emot mycket mera vatten innan genombrott skedde vid återfyllningens front. Denna fördröjning medför en tidsvinst vid återfyllningen innan vatten når fram till fronten. När vatten slutligen bryter igenom sker detta mer dramatiskt genom det innestängda och trycksatta vattnet, som förorsakar stor erosion av material ut från den återfyllda sektionen.

Att hantera vatten och komprimerade luftfickor i återfyllningen bör undersökas ytterligare vid tester i ½-skala under kontrollerade förhållanden, innan mera komplicerade och mindre kontrollerade tester sker i underjordsmiljö.

Installationen och den efterföljande vattenupptagningen av Milos B eller en Friedland lera med hög densitet – Cebogel i en deponeringstunnel med den typen av återfyllning föreslagen i SKB- konceptet, kommer omgående att nå ett svälltryck på tunnelväggen och kommer att nå ett tryck på mera än 800 kPa (800–4,080 kPa) vid låga saltkoncentrationer (inkluderat TDS) på grundvattnet (≤ 1 %). Under högre salthalter (≥ 3.5.% TDS), kommer svälltrycket under konservativa förhållanden att nå gränser på ca 480 kPa för Milos B och ca 840 kPa för Friedland lera. Även vid ett reducerat och utjämnat svälltryck kommer sluttrycket att vida överskrida den gräns på 200 kPa som satts av Posiva.

Vid högt TDS under initialskedet av vattenupptaget, har pellet fyllningen en låg densitet eftersom inget svälltryck hunnit bildas från den kompakterade bentoniten. Under dessa förhållanden blir det en begränsad svällningskapacitet och begränsat motstånd mot vattenflöde och erosion genom fyllningen.

Testerna som beskrivs i denna rapport visar på viss fördröjning av vattengenomströmning i återfyllnaden men tiden beror på ett antal ingående faktorer:

- Storleken på inflödet i tunneln.
- Fördelningen av inflödet (punktinflöde eller fördelat och droppande).
- Geologiska förhållanden (korsande sprickstrukturer).
- Avståndet från inflödet till fronten på återfyllnaden.
- Olika stadier vid återfyllningen (när det är endast en kort väg till fronten, eller senare när det är längre och ett antal mindre flöden samlas till en större kanal i återfyllningen).

Även andra faktorer som trycksatta isolerade luftfickor kommer att påverka vattenupptagningen som medför risk för erosion.

För en torr tunnelsektion med få inflödespunkter (1–2 st), ger ett första uppskattat medelvärde av vattengenomträngning i kontaktytan längs tunnelväggen 1–1.5 m per dag under ett inflöde av ca 0.2–0.25 l/min. Ett högre inflöde kommer att ge en längre genomträngning.

Denna vattengenomträngning är ca hälften av vad som observerats under dessa tester när vatten inflödet kom från endast en punkt och inga sprickor som orsakade fördröjning nedströms (våta partier nedströms från korsande vattenförande sprickstrukturer). Detta indikerar att i en relativt torr tunnelsektion en återfyllning kan ske med en hastighet av 5–6 m/dag vilket innebär ungefär 2–5 dagar innan vatten kan skapa problem vid fronten på återfyllningen. Man bör påpeka att det är en grov uppskattning och olika faktorer kan påverka detta i fält.

Resultat från tester i 1/12 skala genomförda vid Äspö samt tester i ¼ skala genomförda i Finland bör sammanställas och jämföras beträffande material, genomförande och materialets erosionsegenskaper. När detta är gjort kan dessa tester jämföras med de tester utförda i ½-skala som beskrivs i denna rapport för att se om det finns några skalfaktorer som ännu inte upptäckts. När detta är gjort kan det vara värdefullt att utföra ytterligare tester i ½-skala.

Slutligen behövs fullskaliga tester i underjordsmiljö, där berg och hydrauliska förhållanden är att jämföra med miljön i ett slutligt förvar. Tester beskrivna i denna rapport har bidragit med värdefull information som kan användas i planering för en demonstration av tekniken och material för att identifiera vilka tekniska detaljer som ytterligare behöver belysas inför drift i ett slutförvar.

Contents

1 Background

SKB and Posiva are evaluating options for backfilling in their repository concepts for disposal of used nuclear fuel. Their generic approach to repository design involves waste isolation deep underground in crystalline rock. A range of repository design concepts have been developed and the KBS-3V concept selected as the primary reference by SKB includes the use of clay-based sealing materials (buffer) to surround corrosion-resistant canisters containing spent nuclear fuel and also to fill the deposition tunnels as shown in Figure 1-1. Beyond the deposition tunnels, clay-based materials may also be used in backfilling the other excavations associated with the repository (e.g. access tunnels, ramps and shafts). An alternative deposition concept, the KBS-3H (H = horizontal) is also being considered as an alternative to the vertical option and is shown in Figure 1-1. The study presented in this document is focussed on deposition tunnel backfill associated with 3V concept.

The clay materials proposed for use in both the buffer and backfill in the KBS-3V concept are smectite-rich products (typically montmorillonite, but sometimes a mixed layer clay), often sold under the generic product name of bentonite. At present the reference SKB concept for deposition tunnel backfilling involves use of precompacted clay blocks to fill the majority of the tunnel volume and pellets composed of highly compacted clay to fill the remaining volume, shown schematically in Figure 1-2 (Gunnarsson et al. 2006). SKB and Posiva are both considering clay-only materials for use in manufacture of backfill blocks. Additionally, Posiva is considering clay-aggregate mixtures for use in block manufacture (Hansen et al. 2010). This report focuses on clay-only block option.

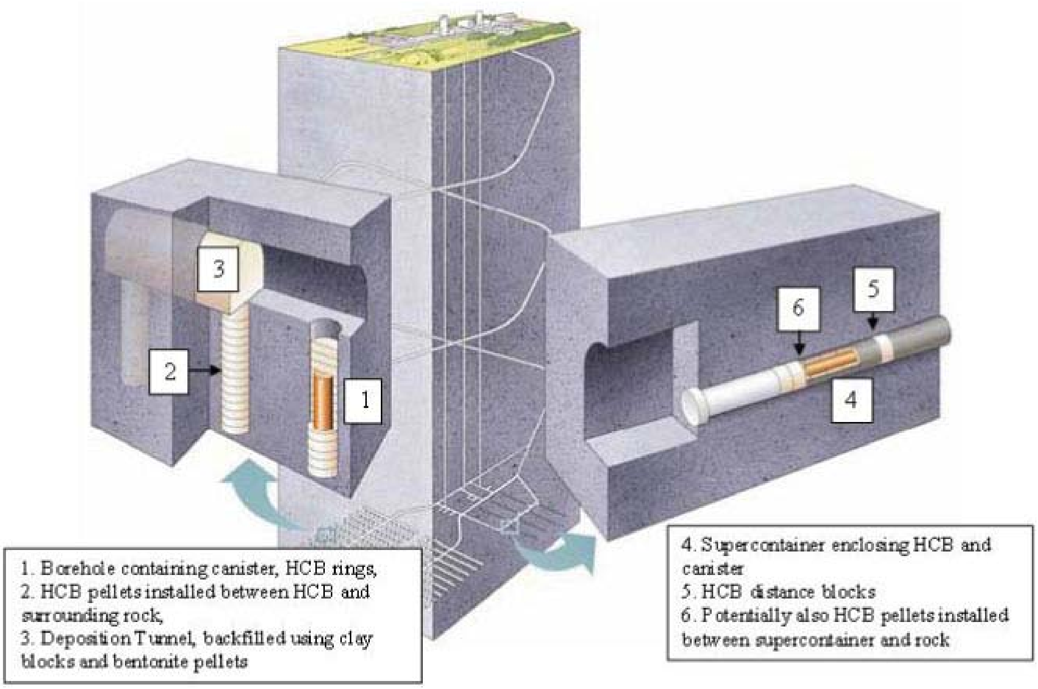


***Figure 1-1.** KBS-3V and KBS-3H emplacement concepts.*

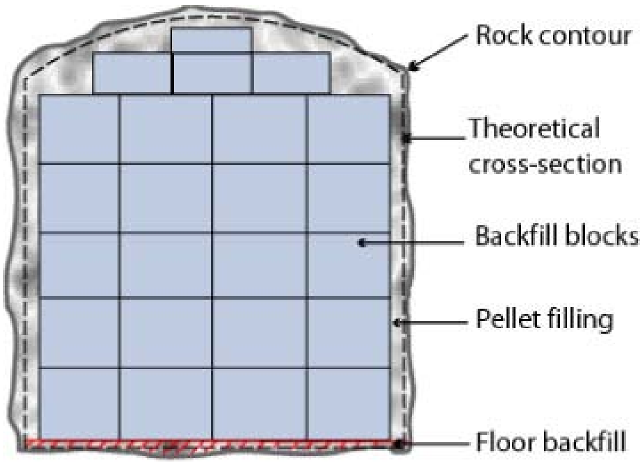


Figure 1-2. *Schematic cross section of a backfilled deposition tunnel (Keto et al. 2009a). The three main components of the block backfill are 1) pre-compacted backfill blocks, 2) pellet filling and 3) material placed underneath the blocks to provide stable foundation for the block assemblage.*

Several basic functional specifications associated with the backfill as a whole have been identified. Assessment of materials options and generic backfilling approaches and then determining how well they met the requirements established for their performance are presented by Gunnarsson et al. (2006). The sub-system functional requirements used to guide this were divided into three categories and the backfill-specific requirements were defined 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.

In order to meet these subsystem requirements, the materials used in the backfill must be able to maintain their specified properties over the long-term. To achieve such long-term performance and aid in the design and assessment of the performance of the backfill, the subsystem requirements are matched to quantitative values derived from the safety indicator criteria defined in the safety assessment SR-Can (SKB 2004). Subsequently the safety functions related to containment were outlined in the SR-Site document.

SR-Site summarised some of the key properties required of the Backfill component as a whole and identified the following items:

- A need to counteract buffer swelling out of the borehole, thereby maintaining buffer density within desired limits (SR-Can Section 8.3.3),
- The buffer should not be a preferred pathway for radionuclide transport and so the following properties are identified as being required.
    - Swelling pressure of >0.1 MPa,
    - Hydraulic conductivity of $< 10^{-10}$ m/s,
    - Temperature of backfill in deposition tunnels must be > -2C.

It should be noted that the above-listed requirements are for the backfill as a whole, there are no clearly defined specifications for the pellet component beyond a need to ensure that the entire backfill remains functional over the long-term. The primary role of the pellet component is to provide lateral support to the blocks, protect them from inflowing/dripping water during the initial stages of system evolution and limit the potential for unacceptable redistribution of the backfill from one region of the deposition tunnel to another by water entering the tunnel. The pellet materials also provide for a greater margin in the functional definitions for the block materials as the pellets occupy volume that the blocks would otherwise have to swell into (especially important in areas with large over-excavated volume). This also means that lower swelling capacity materials could be used in the backfill blocks while still maintaining sufficient swelling-induced forces on the surrounding rock mass and a sufficiently low hydraulic conductivity.

In addition to the performance requirements for the backfill as a whole there are factors that affect backfill design. Specifically, the subsystem requirements concerning effectiveness and flexibility led to development of operational criteria associated with defining adequate rate of backfilling. The backfilling rate required for the deposition tunnels for the KBS-3V concept is 6–8 m in 24 hours for the SKB repository (Gunnarsson et al. 2006), and approximately 5 m per day for Posiva's repository (Keto and Rönnqvist 2007). Any materials and emplacement options considered or developed must therefore be able to be placed at a rate that meets the production requirements established and the installed materials must be physically stable throughout the operational activities.

An important factor in achieving an acceptable rate of backfill installation and having confidence in both its short-term (prior to deposition tunnel closure) and its longer-term performance is defining the installation requirements. There is also a need to know what the installed characteristics of the pellet materials used to fill the gap between the blocks and the surrounding rock will be. It is the pellet material that will see inflowing water first and is relied on to protect the clay blocks from flow-induced erosion during the operating stage of each deposition tunnel. What is needed therefore is confidence that the backfill will remain in-place or at least not substantially degrade locally as the result of erosion. In order to develop such confidence it is necessary to understand how water will enter the pellet-block system and how factors such as inflow pattern, inflow rate, groundwater chemistry, material used in backfilling and potential erosion will affect system performance prior to installation of a deposition tunnel plug. Keto et al. (2009a) provided a summary of some of the key design specifications that will affect installation of precompacted backfill blocks and associated pellet fill in a deposition tunnel and design specifications associated with the pellet fill component of the backfill is provided in Table 1-1. These design specifications impact on backfilling operations and operational planning as there needs to be confidence that water entering already backfilled volumes will not interfere with operations taking place in unfilled regions of the deposition tunnel (e.g. buffer in boreholes not yet holding canisters, ongoing tunnel backfilling operations or construction of deposition tunnel plugs).

Table 1-1. Design specifications related to pellet materials for backfilling of deposition tunnels (after Keto et al. 2009a).

Design specifications required that affect installation of the backfill	
Density	– Average dry density of the backfill must be able to fulfil the function indicators stated in SR-Can, – Acceptable range/variations in dry density, – Bulk density of the pellet filled zone.
Geometry	– Placement of blocks into the tunnel and resulting degree of block filling, – Geometry of pellet filled volume
Backfilling rate	– Installation rate of blocks – Installation rate of pellets
Design specifications concerning materials & manufacturing of pellets	
Pellets	– Material: required amount of swelling minerals/smectite content, smectite composition, other minerals intentionally added, stray materials – Dry density & water content of individual pellets – Granule size or range of sizes (gradation)

Keto et al. (2009b) summarizes the deposition tunnel backfill design for a KBS-3V repository, based on identification of critical processes and technical issues. This summary includes much of the information discussed by Keto et al. (2009a) but also identifies inputs needed to resolve some of the outstanding questions and allow for establishment of clearer design bases for backfill and backfilling (Table Appendix 1). Some of the critical processes and technical issues identified by Keto et al. (2009b) as related to backfill wetting, formation of piping features and their evolution, material installation and aspects of system evolution were examined in the ½-scale tests described in this document. The limitations of the ½-scale mock-up's geometry and the fact that testing was ongoing at the time of preparing the summary by Keto et al. (2009b) meant that many of the items identified could not be addressed by ½-scale tests.

Specifically, those processes related to the following aspects were examined:

- Wetting and formation of piping channels and erosion (establishing pellet layer thickness, effects of inflow rate on erosion),
- Water management (handling of water inflow during backfilling), and to a lesser degree.
- Installation of backfill (especially pellet component).

The tests presented in this document were focused on improving knowledge of the early evolution of a backfilled tunnel where the block and pellet technique is applied. In particular how these materials interact and how fracture features and occluded air affect water entry and saturation of backfilled tunnel were examined. There are a number of other projects that have been completed or are ongoing that are intended to address some of the other outstanding issues related to tunnel backfilling. One that is of particular relevance is the backfill placement trials conducted at full-scale in a simulated tunnel volume (Wimelius and Pusch 2008). That work provides a basis for determining what operational considerations will most substantially affect deposition tunnel backfilling.

2 Evaluation of water movement into and through tunnel backfill: previous large-scale tests

The manner in which water initially moves into and through backfill materials installed in a simulated tunnel section has been examined and discussed by Dixon et al. (2008a, b), Sandén et al. (2008), Riikonen (2009) and summarised by Keto et al. (2009a, b) and Hansen et al. (2010). Those studies examined the potential for point sources of water flowing into an unsaturated section of deposition tunnel backfilled with precompacted clay blocks and extruded bentonite pellets to physical disrupt the backfill.

Testing documented by Dixon et al. (2008a, b) and Dixon and Keto (2009) examined how water initially moves into large pellet-block assemblies (1/12th – and ½ – SKB-tunnel scale (18.9 m^2 cross-section). ¼ – Scale simulations have also been undertaken by Posiva (Posiva tunnel has 14.37 m^2 cross-section) and is documented by Riikonen (2009). These tests examined the effects water inflow rate, permeant salinity, 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 of the tunnel 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 will be described in a separate report currently that is currently being prepared for SKB.

The anticipated groundwater salinity at SKB's proposed repository site at Forsmark only has a TDS in the order of 1–1.5% at repository depth, the regions underlying the proposed repository depth of ~400 m is more saline (up to 3.5%), so a groundwater TDS content of 3.5% is assumed to be present at time of repository construction. The tests completed at Äspö and described in Section 3 focus on conditions anticipated to be present at the repository level of an SKB repository during the installation of deposition tunnel backfill (1% TDS). The tests detailed in this report are also focused on the effects of water inflow pattern and localised wetting on system behaviour during this period. Ultimately it will be useful to examine the effect of higher TDS groundwater on the backfill system at field scale so as to quantify how substantially groundwater composition variations could affect the early stages of system evolution.

The water uptake and movement tests documented by Dixon et al. (2008a, b) focused on examining the behaviour of block-pellet assemblies at 1/12th and ½-scale under conditions that might be encountered at a repository located in Sweden. These trials used precompacted blocks of low smectite content (Friedland clay) and most used high quality extruded bentonite pellets (Cebogel QSE) as the fill between the chamber walls and the clay blocks that occupied most of the chamber. These tests used simulated Äspö groundwater (~1% TDS) as the percolating fluid. The ½-scale tests presented in this report were installed in the same chamber used in tests reported by Dixon et al. (2008b) (Figure 2-1). The new tests were done using two construction geometries, as shown in Figure 2-2 and Figure 2-3.

The Olkiluoto site in Finland is expected to have groundwater TDS at repository depth that is less than 3.5% but under certain conditions could locally reach this concentration. Hence for design purposes this is the salinity assumed to be present in the Posiva facility. Like the Forsmark site being considered by SKB, the deeper groundwater at the Olkiluoto site is more saline than at the repository level (~7% TDS locally versus <3.5% at repository level), but as is the case for the SKB concept, this salinity level is not expected to be a factor during repository operations. Testing of system behaviour at this salinity has also been done on small specimens at laboratory-scale using 7% TDS in order to ensure that even if deeper groundwater should intrude to repository level at a later date that the backfill will perform as required (Section 4.2).

The ¼-Scale test setup used by Riikonen (2009), shown in Figure 2-4 was intended to examine Olkiluoto-specific groundwater conditions (TDS of ~3.5%) and examined blocks manufactured using 100% Friedland clay or 40% AC-200 (activated Milos Ca-bentonite) and 60% crushed rock. The pellets used in the tests consisted of Cebogel QSE extruded bentonite and the flooring materials installed below the blocks was granulated Minelco bentonite. The mineralogical composition and some of the basic behavioural indices of these clay materials are provided in Section 3.

Figure 2-1. *½-scale tunnel simulator located in bentonite laboratory at Äspö (Dixon et al. 2008b).*

Figure 2-2. *½-scale simulation showing downstream face before and after pellet installation. Note the presence of blocks along right side only. Left side contains only 0.15 m thickness of pellet fill between geotextile inner liner and chamber wall.*

Clay Block Assembly prior to pellet installation

Installing clay pellets showing spray nozzle (foreground)

Completed block-pellet assembly

Figure 2-3. *½-scale Tests 3 and 4 showing installed blocks (left) and pellets (right). Note the presence of clay blocks on both sides of mock-up as well as above spacer.*

***Figure 2-4.** 1/4 Scale test cell and assembly at end-of-test (Ekokem tests in Finland (Riikonen 2009)). A similar setup was used for tests described by Dixon et al. (2008a).*

Studies reported by Dixon et al. (2008a, b) and Riikonen (2009) all found that 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). Groundwater composition also has a significant effect on backfill behaviour. Numerous laboratory studies have been done to evaluate the effects of groundwater salinity on pellet erosion (Sandén et al. 2008) and water movement through saturated clay-based materials, including those being considered as potential buffer or backfilling components (Dixon 2000, Karnland et al. 2006, Johannesson et al. 2010). These tests found that as TDS increases, the saturated hydraulic conductivity increases while swelling pressure decreases for a given material and density. These relationships are important as they highlight the importance of groundwater with regards to material properties and potential for erosion.

Differences in the manner in which the Äspö and Ekokem tests (Figure 2-4), were constructed and the boundary conditions initially present (e.g. permeant salinity (1% versus 3.5% TDS); much higher initial degree of wetting of pellet fill in Ekokem tests; manner in which water was supplied and downstream face confinement method and differences in the block and pellet materials used), makes direct comparison of the data somewhat problematic. Some common trends were observed, e.g. initial outflow from test assemblies usually occurred at the pellet-chamber contact and the same type of pellet material was used in many of the tests. Dixon et al. (2008b) 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 (Riikonen 2009), indicate that the boundaries for these three regimes may change depending on test specifications:

1. Where inflow 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 discerned with erosion rate (kg/h), increasing as flow rate increased. 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 along the chamber-pellet boundary.
3. For extreme inflow conditions (inflow rate 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 (kg/h) 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).

3 Tests to examine effects of fracture features and isolated sections of deposition tunnel

3.1 Purpose of tests

In order to have confidence in the long-term performance of the sealing system associated with the KBS-3 repository concept it is important to have demonstrated both an ability to reliably install the backfill and to predict how water will move into and through it. This capability is especially important when evaluating system and component behaviour during the early stages of system evolution when interactions between materials and their surroundings will be most dynamic.

The laboratory-scale, 1/12th-scale and ½-scale tests described above examined how a dry section of backfilled tunnel would react to a point source of water entering it. The manner in which flow rate affects water distribution and in particular how it interacts with the pellet-filled regions surrounding compacted backfill blocks have therefore been investigated to a level where general behavioural predictions could be made. Those tests represented only one possible scenario regarding water movement into a backfilled volume and did not consider the role of more diffuse inflow and subsequent interactions between pellet fill, backfill blocks, entrapped air and features that might facilitate focussing smaller, relatively non-disruptive water flows into a single larger and more disruptive flow.

Two new inflow scenarios were examined in this study and the results are presented in Sections 3.4 and 3.5. Specifically the test layouts examined:

1. In the first layout (Test 1 and Test 2, shown in Figure 2-2), a simulated fracture feature intersects the entire tunnel perimeter (excepting floor). Water was supplied to the fracture at a very low rate and water uptake and movement away from this feature were monitored. Two rates of water flow into the tunnel via the fracture feature were examined (0.1 l/min and 0.25 l/min).
2. The second geometry, used for Test 3 and Test 4 (Figure 2-3), involved examination of how intersecting fracture feature(s) could generate a local “gasket-like” feature that effectively isolates a section of tunnel. How this would affect subsequent water movement into and through the isolated zone was monitored. Fracture feature(s) that supplied small amounts of water to the perimeter of the tunnel over a fairly narrow (~10 mm-wide), region, were coupled with subsequent water influx from two (2) point sources further up the tunnel (simulating a total of 0.2 l/min water movement towards the downstream face from deeper in the backfilled tunnel via piping features at the rock-pellet contacts). The gasket-like feature in the pellet fill effectively isolated the region upstream of the fracture from the region downstream. The manner in which the tunnel backfill reacted to isolation of section(s) of tunnel was monitored. This simulates situations where a number of small, water-bearing fractures that intersect the deposition tunnel generating a number of “isolated” sections of tunnel.

3.2 Materials examined

The four tests done in this study were built using bentonite blocks and extruded pellets manufactured from non-actived Milos B bentonite (Figure 3-1). This material is a natural calcium-bentonite which has undergone no sodium activation (e.g. to convert it to a sodium bentonite used in manufacture of Cebogel pellets). The blocks are of the same dimensions as previously used (300 × 150 × 75 mm) for tests done using Friedland Clay blocks and Cebogel QSE pellets (Dixon et al. 2008a, b). The Milos B blocks were compacted to a dry density of 1,650 kg/m^3, which is somewhat lower than the Friedland blocks used in previous ½-scale tests (Dixon et al. 2008b, Keto et al. 2009a) but this lower dry density was compensated for by the higher swelling clay content of the Milos B material.

This test series, using Milos B bentonite rather than the Friedland clay used in previous ½-scale tests, was undertaken to examine the effect of using a higher-smectite content clay to manufacture blocks for use in deposition tunnel backfilling.

Figure 3-1. *Photos showing pellets and blocks manufactured from Milos B bentonite.*

It is important to note that previous ½-scale tests (Dixon et al. 2008a, b), used Friedland clay, which has a lower and reportedly variable (~25–45%) smectite content (Table 3-1). The blocks used in those tests were also manufactured to a density substantially lower than intended (1,820 kg/m^3 rather than the intended 2,000 kg/m^3), which will affect the longer-term swelling pressure developed by and hydraulic conductivity of, the backfill but should not substantively affect the shorter-term initial wetting behaviour of the backfilled tunnel. Care does however need to be taken when comparing the results of the previous test series (Dixon et al. 2008b) to those presented for Milos B materials used in the tests described in this document. The use of higher density Friedland blocks in the deposition tunnels would likely result in similar behaviour to the higher smectite content, but slightly lower dry density Milos B materials. Details of their anticipated behaviour is discussed in detail later in this report.

Table 3-1. Basic mineralogical information on clays examined.

Material	Potential application	Swelling mineral content of swelling minerals	Main accessory minerals	Reference
Friedland clay	Block material	Mixed layer illite-smectite (montmorillonite) / range 25–34%, mean value ~30% determined with Siroquant analysis	Illite, quartz, kaolinite, muscovite, plagioclase, pyrite	Karnland et al. (2006)
		Mixed layer illite-smectite / average value 45%	Quartz, mica, chlorite, feldspar and carbonate	Pusch (1998)
		Mixed layer illite-smectite	Quartz, kaolinite, chlorite, plagioclase, K-feldspar, illite, and pyrite	Carlson (2004)
Milos B bentonite (IBECO-RWC-BF)	Block material (100% clay blocks),	Estimated montmorillonite content ~50–60%	Not reported	Keto et al. (2009b)
	Pellet material	Montmorillonite Sample 04: 58% Sample 08: 70%	Illite, mixed layer clays, kaolinite, feldspar, carbonates, pyrite	Olsson and Karnland (2009)
Cebogel pellets (Milos activated Ca-bentonite)	Pellet material	Montmorillonite 80%	Quartz, feldspars, calcite and dolomite	Ahonen et al. (2008)

The Milos B bentonite used in this project has previously been assessed with respect to its basic mineralogical composition and data is provided in Table 3-1. As can be seen in this table, the Milos B bentonite is also subject to considerable mineralogical variation, which might affect the swelling and hydraulic behaviour of backfill manufactured using this clay.

Since Friedland and Cebogel QSE bentonites were used in previously reported ½-scale tests (Dixon et al. 2008b) and so are also extensively referenced in this report, their basic mineralogical compositions are also included in Table 3-1.

3.3 Test setups

3.3.1 Physical setup of tests

The operation of the current series of tests utilized previous experience with the 1/12th- and ½-scale mock-ups in selection of its components, physical construction and operation. Some of the key assumptions and justifications for the setup selected are provided below. Being a mock-up and lacking some of the features and processes that would be present in a natural environment there are of course some limitations in terms of how these tests were operated. Primary among these for the series of tests described in this document are the presence of a smooth contact between the pellets and the chamber wall; the dimension of the gap between the blocks and the chamber wall; the method of construction of the mock-up and the application of water to the system.

Nature of interfaces present in the mock-ups and gap between components

There are of course 3 major interfaces of interest in these tests; the pellet-chamber wall; the pellet-clay block and block-block contacts. The ½-scale chamber provides a very smooth contact with the pellet materials and hence is likely to provide an easier pathway for water flow along this interface. The result should be results that are more conservative with respect to breakthrough pressures and ease of formation of piping features. A natural rock surface would likely provide higher resistance to water flow along the interface and might tend to encourage move water movement towards the block materials. In contrast, the excavation damaged region (EDZ) on the surface of the rock walls in a excavated tunnel are potentially preferred pathways for water movement and could at least locally largely bypass the pellet fill or at least provide for a more dispersed wetting of the pellets. Both of these processes can only be effectively evaluated in a field trial under natural rock conditions although there is some work that is being done to evaluate water movement from rock blocks into the granular clay materials proposed for use as tunnel flooring below the clay blocks. The results of these tests have not yet been published and may have some applicability to the nature movement in the sidewall and crown regions of the tunnel backfill.

Previous mock-ups done to evaluate the pellet-clay backfilling concept have shown a that water movement typically occurs along the pellet-chamber wall but in some situations may also occur along the pellet-block contact. Depending on the materials used and the rate of water inflow, the water flowing through the system can be either erosive or non-erosive.

The presence of joints between the clay blocks are the pathways identified as being potentially vulnerable in clay blocks constructed using low-density (1,820 kg/m^3) Friedland clay (Dixon et al. 2008a, b). The use of a block material of less-than-ideal density and relatively low swelling clay composition could, under some inflow conditions, experience erosive water flow along the contacts between the blocks (Dixon et al. 2008a). These tests also had a narrow (~0.1 m) band of pellets installed between the blocks and the chamber wall which was therefore a potential issue with respect to the robustness of the pellet fill as a protective layer around the blocks.

In previous tests it was suggested that increasing pellet-layer thickness to ~0.15 m seemed to be sufficient to protect the blocks from detrimental hydraulic processes under modest inflow rates. Water tended to move gradually and non-disruptively from the perimeter inwards towards the blocks. This was also the experience in the tests described in this report. In the current set of tests, the Milos B bentonite contains a substantial swelling clay component and is compacted to a sufficiently high density to be capable of applying substantial compressive force on adjacent materials.

Construction of mock-ups

The 4 tests done in this study all have exactly the same gap width along the walls of the chamber (0.15 m), which is comparable to the previous ½-scale tests described by Dixon et al. (2008b). The gap between the top of the block assembly and the chamber roof was approximately 0.2 m although slight variations occurred between each test. These parameters were fixed so as to minimize the number of variables that could affect the results obtained by the tests and also represented an approximately 80% block filling degree. The gaps also represented a readily workable dimension with respect to installation of the pellet materials. It is possible to construct systems with smaller gaps by varying the basic block placement layout (previous work by Dixon et al. (2008a), Riikonen 2009) and tests ongoing in Finland using the same setup as shown in Riikonen (2009)), or by using a flexible block installation method that allows for additional blocks to be installed in regions with high over-excavation. Such setups will allow for further evaluation of the effect of gap width but is outside the scope of the tests described in this document. One of the goals of the current studies was to construct a geometry where the blocks were effectively protected during the initial stages of water inflow and this was accomplished through use of a 0.15 m – thick pellet fill along the walls of the chamber. Ultimately field trials located underground will be needed in order to definitively determine what is necessary in terms of gap dimensions.

The current test series also did not use a flooring layer of crushed bentonite in their construction. The decision to eliminate this component was based on previous test results (Dixon et al. 2008b), where this component was not observed to play any discernible role in water uptake or movement in the geometry being evaluated. As the mock-ups did not include any water supply from the floor it was decided that this component was not necessary for the current set of tests.

The mock-ups constructed for this test series were all constructed using a central formwork that occupied the majority of the volume of the chamber as can be seen in Figures 2-2 and 2-3. There were a number of reasons for this construction including:

- The use of a very rigid assembly of blocks to fill the majority of the chamber put the chamber at risk of physical failure due to the high swelling pressures developed once blocks started to saturate (see Section 4.2.2);
- The tests were intended to examine the early stages of water movement and the internal blocks would not play any substantive role in this (results from previous ½-scale tests demonstrated this);
- Use of blocks in core of mock-up would have been costly and un-necessary (based on point above);
- The construction allowed for rapid dismantling of the mock-up and capture of the end-of-test hydraulic conditions; and
- A solidly-filled block assembly would have some initial compliance due to the presence of construction gaps and joints between the blocks. This was in-part simulated by the limited capacity of the internal framework to deform.

Application of water to mock-ups

The use of a mock-up always induces some limitations to the interpretation of the tests, one of these relates to the application of water to the system. In the current set of tests the mock-up was constructed before water was supplied to the rear of the chamber. In some field situations where there is little water inflow or inflow is very dispersed, the construction of the mock-ups may not have been substantially different from actual conditions. If the repository conditions are such that there are considerable locations where point inflows occur, the utilisation of the results of the mock-ups should be carefully assessed.

The construction of the mock-ups have shown that it is possible to rapidly install the pellet fill once the blocks are in place. Placement would therefore be little affected by the presence of low inflow, or seepage-type features in a repository. Current repository operations concepts also include recognition that there may need to be installation of some form of water diversion/collections at major inflow points and these would simulate to some degree that was present in the mock-ups. The presence of ongoing, uncontrolled and uncollected inflow in a deposition tunnel will be problematic as it will affect all aspects of the backfilling process from placement of bentonite on the floor through block installation and pellet placement. If a situation existed where a very high local inflow feature is encountered it is also going to be necessary to remediate that location so that inflow is reduced, controlled or collected during tunnel operations. Once tunnel closure is accomplished, the presence of such a feature becomes less important with respect to the potential for localised erosion of the backfill.

3.3.2 Materials and material installation

The clay pellet component for all the tests presented in this document was installed with the addition of water at the nozzle of the shotcrete hose during blowing of the pellets into place (construction water). The same method was used in the majority of the ½-scale tests reported on by Dixon et al. (2008b) and illustrated in Figure 2-3. This allowed the pellets to be placed as a cohesive mass that was nearly vertical at the downstream face of the pellet-filled volume and did not require downstream mechanical support to keep them in place. It also minimized the potential for pellet settlement in the crown regions, which would otherwise have occurred when using dry granular materials.

The quantity of water added during the pellet placement process (construction water) for each test is presented in Table 3-2. It ranged from 70 l to 740 l depending on the volume of the construction (Test 4 was 50% larger than the other 3 tests and had the highest quantity of water used in its construction). The amount of water added meant that the majority of the pellet filled volume did not have a high degree of initial saturation (20–35%). This means that the pellet fill initially had an open structure into which water could flow with minimal initial resistance and hence air could also move through the as-placed fill in an essentially unhindered manner. The region immediately around the downstream face of the construction was installed with an intentionally higher water content, resulting in a much higher degree of initial pellet saturation and a tendency of those materials to swell and produce a more gas/water resistant downstream face for the assembly. Based on the hydraulic pressures required to induce flow out of these tests this wetter face did not substantively alter system hydraulic behaviour. The variation in the amount of construction water utilised in these tests was associated with difficulty in ensuring that the same rate of water supply to the nozzle occurred for each construction (operator dependent) and also differences in operator method used in filling chamber.

Tests 1 and 2 examined the role of a through-cutting, water-bearing feature that was the dominant source of water supply to the tunnel on subsequent water uptake and movement.

In Tests 3 and 4, artificial fracture features on the walls of the chamber were allowed access to water at very low rates of supply for a very limited period of time. This simulated the presence of a fracture that is seeping only very slowly and the timeframe when there is essentially no water-flow into the regions immediately beyond (up-tunnel) from that feature. This “prewetting” water quantity is provided in Table 3-2. After a brief period following test construction the main water lines were turned on and the mock-ups were supplied with “inflow” water.

The dry density to which the clay pellets were installed in the current series of tests (840–920 kg/m^3) was lower than the target of 1,000 kg/m^3 target set for these installations. There are several reasons why this may of occurred, such a inadequate line pressure in the spraying machine, operator inexperience with the materials, the distance between the spraying nozzle and the back of the chamber, as well as the nature of the material installed (size, shape, durability and density of the individual granules). This listing of variables that can substantially affect as-placed density highlights some areas where refinement in the material placement procedure are needed. The issues of pellet size, shape, density and durability are the topic of a joint SKB-Posiva-NWMO project scheduled for conduct in 2011. In the tests described in this document, the presence of a lower than intended as-placed density for the pellet fill would likely not have substantially altered the general results, although it may have resulted than a slightly less resistant material to water inflow and gas movement than intended. The use of a block materials such as Milos B clay or high-density Friedland clay would have meant that lower than expected pellet densities would be compensated for by the high swelling capacity of the blocks. This issue is discussed later with respect to swelling pressure and hydraulic conductivity of the system (Section 4.1). Specific issues are discussed as part of presentation of each test.

Table 3-2. Details of materials installed in ½-scale tests.

	Test 1	Test 2	Test 3	Test 4
Test Assembly Length (m)	3.9	3.9	3.9	5.45
Flowpath Length (m)	1.9	1.9	3.9	5.45
Volume of pellets and blocks (m^3)	8.281	8.281	11.339	15.791
Mass of pellets dry (kg)[+]	4,627	4,714	3,319	4,866
Width of pellet-filled gap (m)	0.15	0.15	0.15	0.15
Volume of pellets installed (m^3)	5.102	5.102	3.955	5.526
Average pellet fill dry density (kg/m^3)	910	920	840	880
# blocks installed	767	767	2,054	2,844
Dry mass of blocks installed (kg)[++]	4,271	4,271	11,438	15,838
Volume of blocks installed (m^3)	2.641	2.641	6.933	9.688
Estimated construction water, L	199.7	NM	293.5	740.6
Estimated start of test saturation of pellet fill % **	~20	~20	~23	~35
Prewetting water (T3, 4) (L)	–	–	18.1	46
Inflow rate (l/min)	0.1	0.25	2 × 0.1	2 × 0.1

[+] As-recieved pellets had gravimetric water content of ~ 13%.

[++] Blocks had a initial as-received dry density of 1,650 kg/m^3.

* Downstream face was intentionally installed wet (~saturated) in order to provide a tight downstream seal on each construction. Values assume 0.15 m deep saturated zone of pellets at downstream face and uniform distribution of water through remaining pellet-filled region.

NM – quantity of water logged during placement was not sufficient to achieve known as-built conditions, a malfunction in guage is assumed. Conditions are expected to have been similar to those in Test 1.

The tests assembled for this study were monitored to determine:

- Rate of water supply.
- Resistance to inflow at inflow points.
- Time at which water exited chamber for the first time.
- Subsequent changes to outflow location.
- Amount of water exiting the chamber.
- Quantity of solids removed (where possible).
- Nature of flow path at end of test by using visible dye to inflow water.

During dismantling, water distribution was visually determined and physical features associated with water movement or material removal were noted. Previous ½-scale tests found that physical sampling of the pellet and block materials during test dismantling was of limited value and visual assessment provided a better means of determining where water had moved during the test operation. As a result extensive photographic recordings were made as the tests were stepwise dismantled and these were used to determine where water uptake and movement were occurring during the period immediately following backfill placement.

The quantities of materials installed in each of these tests are provided in Table 3-2 along with a summary of the initial conditions present. Specific details associated with each test are provided in Section 3.4 and are summarised in Section 4.

3.4 Simulation of water inflow from intersecting fracture or into hydraulically-isolated tunnel section (Tests 1 and 2)

The ½-scale Tests were operated in a steel chamber constructed in the Bentonite Laboratory at SKB's Äspö facility. The test chamber was constructed in a manner such that its cross-section was nominally ½ that of an emplacement tunnel that would be present in an SKB repository using the KBS-3V concept for in-floor canister installation.

Figure 3-2 shows the layout of the ½-scale chamber shown in Figure 2-2, with the water inlet points identified. In the test series described in this document, the uppermost 3 ports (elevations 1.5 m (2) and 2.75 m) at 2 m and 4 m distance from the rear of the chamber were used to supply the simulated fractures. Tests 3 and 4 also utilized ports at the rear of the chamber to provide water into the isolated sections of the tunnel. The inlet ports at the rear of the chamber enter from the end of the chamber at elevations of 1.8 m (left side) on the left side and 0.3 m (right side). These supply lines are 0.07 m from the outside edge of the chamber's back wall and extend only about 50 mm into the chamber and so are initially surrounded by pellets and are equidistant between the blocks and the outside wall of the chamber (Figure 3-2). Water was supplied to the test via constant-rate-of-flow pumps, each of which could be preset to supply different rates of water to the test. The chamber length is 6 m but only 4 m was utilized for Tests 1, 2 and 3 with the fracture located at the midpoint of the backfilled volume. For Test 4 the length of the assembly was increased to 5.45 m in order to provide for construction of two fracture features within the chamber and thereby allow for examination of sequential breaching of isolated tunnel sections.

3.4.1 Test 1: Inflow rate of 0.1 l/min

The first two tests conducted as part of this study examined the effect of a narrow (~20 mm wide) fracture that vertically intersected a backfilled tunnel and was supplying water at rates of 0.1 and 0.25 l/min along the entire perimeter of the tunnel (excepting the floor). The geotextile was fed water at three different points (left side, right side and crown) of the perimeter in order to simulate how water would likely be able to entire a tunnel from a fracture that has high hydraulic head but limited rate at which water can move through it. In such a system the swelling of the backfill might be able to locally plug the location where water inflow occurs but this inflow would likely just shift to other locations where entry to the tunnel was not so effectively inhibited.

Figure 2-2 shows the layout of Tests 1 and 2 (fracture feature shows as purple feature in photos due to use of indicator dye to identify flow path(s) at the end of test operation). These tests were identically constructed, with backfill blocks and pellets installed on the right side and only pellets on the left and crown regions. This setup is comparable with that used in previous ½-scale tests (Dixon et al. 2008b) where it was established that initial water movement into and through the backfill is controlled by the pellet fill and the presence or absence of block materials does not substantively alter the results obtained. In order to have comparability to previous tests, the geometry previously used was maintained. This setup is not entirely representative a tunnel where blocks will fill the majority of the tunnel volume and where the blocks will have a greater influence on the degree to which the pellets are compressed and how the materials at the perimeter of the tunnel will behave (see further discussion in Section 4.1). For the purposes of evaluating the initial behaviour of the backfill the setup was judged to be reasonable.

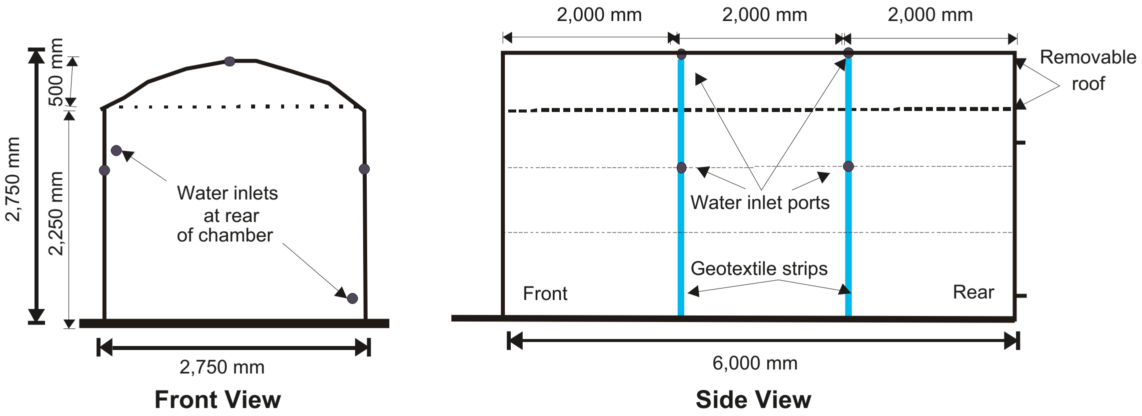


Figure 3-2. *Schematic of ½-scale chamber showing location of water inlet ports used to supply the artificial fracture.*

Tests 1 and 2 occupied 3.9 m of the simulators length and the simulated fracture feature was located at a distance of 1.9 m from the front face of the construction. The tests were monitored to record inflow rate, outflow rate (if possible), outflow location(s) and time at which outflow began. At the end of the test a blue food dye was mixed with the inflowing water to make the active water flow path(s) visible as dismantling occurred. This dye was selected as it was non-toxic and had sufficient sorptive capacity to remain visible on clay it contacted.

Test 1 supplied the backfilled chamber with simulated Äspö water (1% TDS) at a rate of 0.1 l/min to the simulated fracture. This wetting continued for a period of 40 hours (~240 l of water input), before water began to exit the assembly via a small flow feature in the upper left region of the assembly. Water exited as a small trickle that was located at the pellet-chamber boundary and subsequently flowed down the downstream face of the assembly, generating a wetter and better-sealed front face in that region (see Figure 2-3. Although outflow was occurring, approximately 60% of inflow volume was still being absorbed by the assembly at the end of 300 hours of testing, resulting in the formation of a band of nearly saturated pellet materials around the entire perimeter of the chamber and the start of backfill block saturation and swelling as can also be seen in Figure 3-3. For illustrative purposes a sketch showing the evolution of water flow in Test 1 is also provided in Figure 3-3.

The water that exited the test assembly was clear and contained no measurable clay content (Figure 3-4). It was also noted that the exiting water did not result in any discernible deposition of material at or immediate beyond the downstream face of the mock-up. The water supplied to the backfill was very uniformly absorbed by the adjacent pellet (and block) materials, with absorption being the dominant process for water migration. This is consistent with previous observations where water was supplied slowly (0.1 l/min) at a discrete location at the pellet-chamber contact and supports a conclusion that low inflow rate will have minimal effect on the short-term physical stability of the backfill.

An inflow rate of 0.1 l/min is still apparently more than the pellet fill can absorb on its own during the initial stages of backfill wetting. Based on the outflow captured in this test, the pellet fill is only able to absorb approximately 0.06 l/min with the remainder being forced to move towards the downstream face of the backfilled volume. It should also be noted that water entering the tunnel via such a fracture feature is actually spread over a much larger contact area than is the case for water entering via a discrete entry point. Hence as the contact area increases, it could be expected that a greater proportion of the water entering the tunnel could be drawn into the pellet fill and as a result, time before sufficient resistance to outflow develops to drive water downstream into unsaturated regions would increase. This means that where fracture features intersect a tunnel, the threshold inflow rate before advective flow becomes a concern should increase, providing more time before water makes its way to the downstream face.

The resistance to water inflow for Test 1 was also very low (Figure 3-5) but gradually increasing as the test progressed. This is attributed to the gradual wetting of the materials immediately adjacent to the fracture feature, associated development of swelling pressures and development of lower permeability in the wet region. The water would need to gradually increase its pressure in order to overcome the increasing compression by adjacent materials; this is consistent with previously completed tests at 1/12th- and ½-scale.

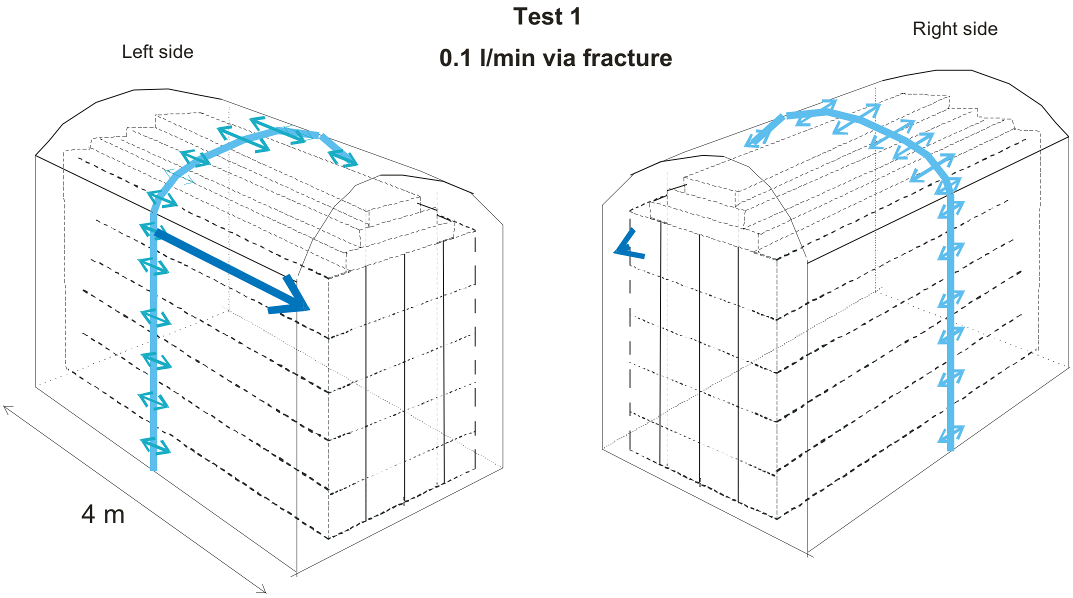
3.4.2 Test 2: Inflow rate of 0.25 l/min

Test 2 differed from Test 1 only in the rate that the simulated fracture was supplied with artificial Äspö water (0.25 l/min versus the 0.1 l/min in Test 1). Previous tests done at 1/12th- and ½-scale indicated that at 0.25 l/min there was erosion of pellet materials when water moved along a single flow path. Those tests also showed that wetting was initially less extensive at this inflow level with only a limited region around the flow path initially experiencing water saturation.

Test 2 had the 0.25 l/min supplied via the same three perimeter ports (connected via geotextile "fracture" feature) as were used in Test 1. Water uptake was limited (~15 l in first 90 minutes of operation) before water began to exit the chamber along the pellet-wall contact at the floor of the chamber on the left side. Discharge from this location was very limited (a few 100 ml) and at approximately 18 hours small amounts of water began to exit the backfill at the upper left quadrant where the chamber roof met the side wall. Again outflow from that location persisted only a few hours before it ceased and shifted to a third location. At 42 hours outflow began at the floor level on the right side at the pellet-wall contact. As was the case with the other outflow occurrences, this flow only continued for a short time and was of very limited volume.

Flow path for water at upper left (Dark feature)

Artificial fracture at mid-point of Tests 1, 2 (coloured by dye)



Wetting at location of artificial fracture resulted in gasket-like seal extending through first row of blocks.

***Figure 3-3.** Water movement into and through pellet-filled region in Test 1 (0.1 l/min).*

***Figure 3-4.** Water that exited Test 1. Water was clear and lacked discernible sediment.*

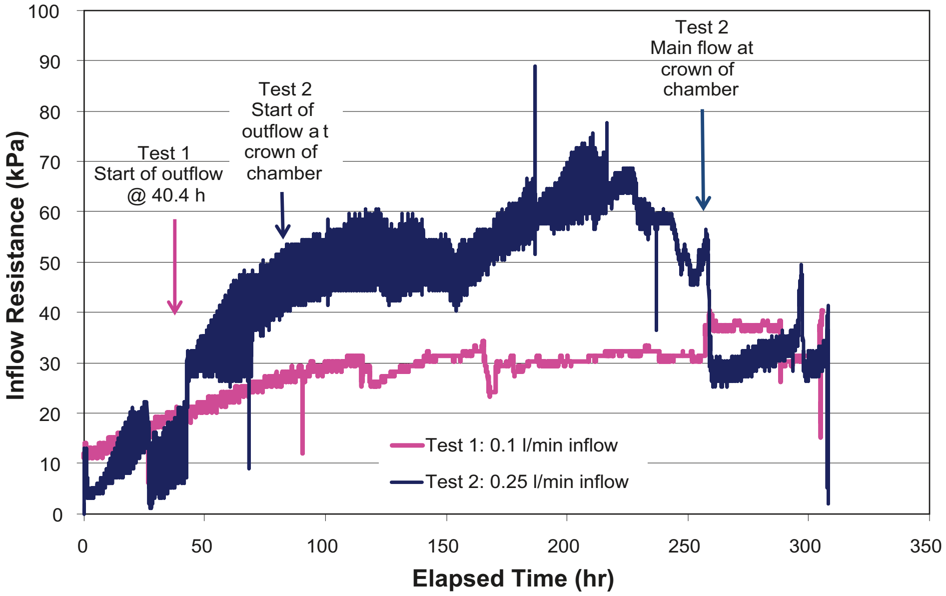


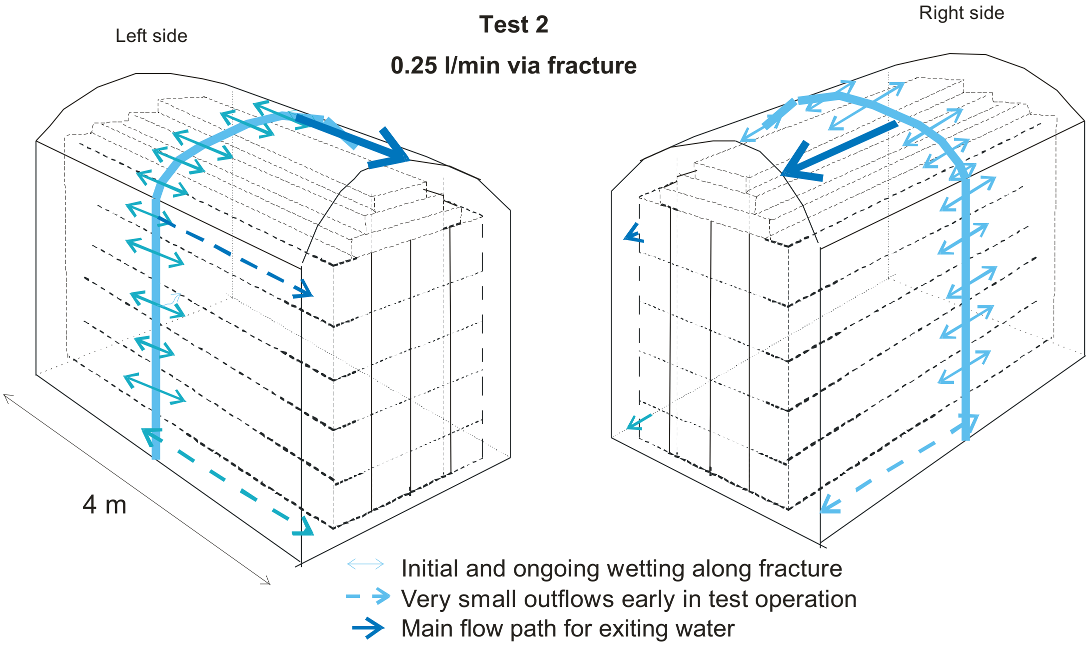
***Figure 3-5.** Backfill-induced resistance to water inflow for Tests 1 and 2.*

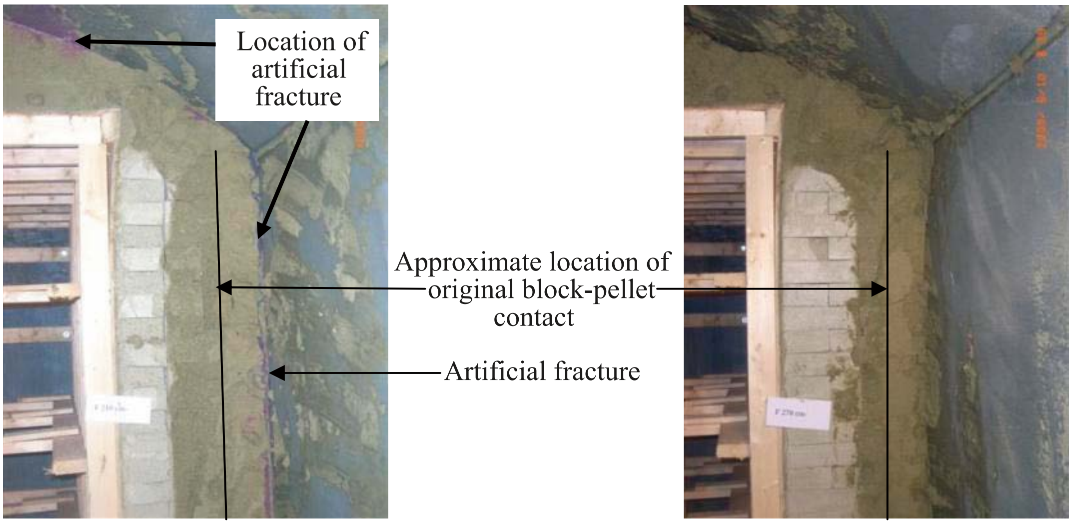
At 77 hours into the test a major flow path developed at the crown of the chamber (slightly to right of center, Figure 3-6) and water exited the backfill along this pathway for the remainder of the test. At 77 hours approximately 1,155 l of water had entered the backfill and very little had exited. A slightly increasing rate of outflow from the crown region time of its initiation until approximately 220–260 hours was observed. Associated with this was a decrease in resistance to water inflow from ~70 kPa to ~30 kPa. By ~260 hours of testing, outflowing water had generated an open pathway (material could be eroded at the same rate as they swelled into the flow path and near steady-state flow was achieved (inflow resistance ~30 kPa). At 30 kPa inflow resistance at the end of test, this test is showing behaviour that is comparable to what was previously observed for systems having water supplied by a single inflow point (Dixon et al. 2008b, Keto et al. 2009a). A schematic showing the interpreted evolution of flow paths within the test is provided in Figure 3-6.

The maximum resistance to water input to the chamber was low ~70–75 kPa. The use of higher smectite content block materials in these tests relative to the previous test series (see Table 3-1) should result in higher swelling pressure being developed in the regions immediately adjacent to the fracture feature and hence an elevated resistance to inflow might be expected.

Outflow from top right area of crown
Blue dye shows exit point

Pellet materials eroded from mock-up





Wetting at location of fracture

60 cm downstream from fracture
block wetting is not as extensive

Figure 3-6. *Water uptake by and flow through Test 2. The water supplied to the artificial fracture has penetrated approximately half-way through clay blocks. At end of test outflow is slightly to the right of the crown along the pellet-chamber contact.*

Erosion of pellet materials by the flowing water was minimal until the development of the flow path along the roof of the chamber, at which time discernible quantities of sediment began to be discharged (see Figure 3-6). It should be noted that the quantity of material actually lost was actually relatively small, in the order of 0.13 kg/h and only after the outflow began at the crown of the chamber. Again this level of erosive activity is comparable to that observed for single-point inflow tests and indicates that water will tend to move along a limited number of pathways, regardless of how it enters the backfill.

In Test 2, physical swelling of the pellet and block materials in the interior of the mock-up definitely occurred with dry blocks near the top of the assembly on the right side being pushed several centimetres in the downstream direction (Figure 3-7). This will have relieved some of the swelling-induced compression at the cell wall but would likely not have been sufficient to account for the low resistance to flow observed. Of more importance is that the crown regions of Tests 1 and 2 did not contain a block fill component and so swelling pressure in that area would have been low (discussed in Section 4.2.2). The crown region represented the path of least resistance to flow and that is where ongoing outflow developed.

Deformation of the downstream face of the mock-up observed in Test 2 has been observed to lesser degrees in some previous tests and highlights a potentially disruptive process for tunnel backfilling in a field application. It is of particular relevance when there has been suspension of backfilling operations for an extended time and the swelling of the clay upstream from the face has progressed to a significant extent. The overall stability of the backfill may not have been compromised by the presence of a non-uniform backfill face but it could make resumed operations problematic. It will be difficult to deal with an uneven downstream face in such a way that the backfill retains a uniform degree of block fill per m-length of tunnel. Depending on the degree of deformation of the downstream face, considerable remedial effort may be needed before backfilling can resume.

Test 2 was carefully dismantled in order to observe water distribution and to identify flow paths developed in the course of 12 days of water inflow via a simulated fracture feature. Figure 3-6 shows the distribution of water within the backfill pellets (and clay blocks) at the location of the fracture feature. In total there was ~1,155 l of water uptake before outflow and a further 860 l stored within the backfill after outflow began (total of 2,015 l). This is substantially more than the ~1,200 l of total uptake by Test 1. In Test 2 there is also evidence of much more extensive wetting of the backfill block materials, especially adjacent to the fracture features (Figure 3-6). This wetting and swelling of the pellet and block materials adjacent to the fracture feature has generated a near-continuous belt of saturated material adjacent to the tunnel walls. If such features are generated within a deposition tunnel, they could result in the development of isolated pockets within the tunnel. Such features have the potential to have considerable gas pressure developed within them as water subsequently enters

***Figure 3-7.** Swelling of blocks resulting in localised deformation of ~50 mm at downstream face of Test 2. Deformation was the result of swelling of clay blocks in vicinity of the artificial fracture.*

the isolated region and air is unable to escape. Development of pressurized pockets within the tunnel and their subsequent venting into adjacent sections of tunnel have the potential to be disruptive to backfilling operations should they extend to the working face of the backfilled tunnel. In order to examine the potential for such a process to develop, Tests 3 and 4 were undertaken.

3.4.3 Summary of results from Test 1 and Test 2

The behaviour observed in Tests 1 and 2 indicate that water entering a tunnel via a cross-cutting fracture feature will initially move uniformly into the pellet fill along the entire contact area. As adjacent pellet materials wet and provide increased resistance to further inflow the incoming water begins to concentrate into a limited number of flow features as it seeks pathway(s) offering lower resistance to flow. This results in development and abandonment of flow paths in the early stages of water uptake. Eventually a single pathway develops and the majority of the incoming water subsequently moves along the pellet – wall contact along that route, although some continued water uptake by the pellets continues throughout the test (~0.06 l/min based on data presented in Table 3-2). The rate at which Test 2 was able to absorb inflowing water (0.06 l/min) following development of a preferential channel is the same as was observed in Test 1. This is comparable with results obtained for previous ½-scale tests where a single inflow point with ongoing wetting (and increasing degree of system saturation), it is expected that the proportion of advective transport would increase but these tests did not operate long enough for this to be confirmed.

Tests 1 and 2 each operated for more than 300 hours (~12 days) with no substantial structural disruption and only minor erosive action (nil and < 0.13 kg/h (~8.7 g/L of outflow) removal for Tests 1 and 2 respectively) once outflow was occurring. There was limited localized deformation of the block fill in the region close to the main outflow pathway in Test 2 but this did not seem to have affected system behaviour. The overall stability of the system is therefore not likely to be compromised by the presence of a single flow feature providing 0.25 l/min (or less). These two tests also demonstrated the change in system behaviour from one where inflow was largely accommodated by water absorption into the pellet fill (~60% of inflow at 0.1 l/min was absorbed by backfill) for the period immediately following the installation of the backfill (first couple of weeks) to a system where inflow exceeded the ability of the system to absorb it (~24% of inflow at 0.25 l/min). The higher inflow condition resulted in a more heterogeneous wetting pattern as the excess water initially sought to exit the backfill along several pathways.

3.5 Simulation of flow into isolated section(s) of tunnel

In Tests 1 and 2, it was observed that water entering the tunnel via an intersecting fracture resulted in formation of a gasket-like swelling of the clay pellets around the perimeter of the tunnel. This gasket has the potential to affect how subsequently supplied water will move within the tunnel. The main purpose of Test 3 and Test 4 was therefore to evaluate how water flowing into a backfilled tunnel section would be affected by a pre-existing "gasket" of pellets.

Test 3 and Test 4 were constructed in the same manner, with a 300 mm – thickness of blocks assembled along both sides of the assembly, providing uniform distribution of blocks and pellets in all regions of the assembly (Figure 2-3). In these tests it was important that there be uniformity in the geometry of the block and pellet fill. This allowed for interaction of the pellets and blocks to be assessed with respect to the development of isolated volumes and their subsequently saturation. In Test 3 only 4 m of the chamber length was utilized, resulting in the single fracture feature being located approximately 2 m from the downstream face of the backfilled chamber. In Test 4 the length of backfilled volume was increased to 5.45 m in order to provide for construction of two fracture features (at 2 and 4 m) and two isolated pockets within the chamber.

In Tests 3 and 4, water was supplied to the same type of artificial fracture feature as was used in Tests 1 and 2 of this study. However in Tests 3 and 4 these features were supplied with water at a much lower rate (0.0025 l/min versus 0.1 l/min) for a relatively short time (120 hours) in Test 3, while Test 4 was allowed to absorb water for 312 h before inflow was initiated. At the end of the seepage stage, the water supply to the simulated fracture(s) was discontinued and the two ports at the rear (left and right side) of the chamber were used to provide water to the isolated sections of the tunnel.

3.5.1 Test 3: Effect of a single simulated fracture on subsequent water movement into backfill

In Test 3 the simulated fracture feature present in Tests 1 and 2 was supplied with 0.0025 l/min (0.15 l/h) simulating a slowly seeping fracture where inflow is so low that remediation is unlikely to be necessary. The fracture was allowed to provide water to the pellet fill for 120 hours (total inflow ~18 l) before water was supplied at 0.1 l/min at both the left and right rear sections of the chamber (total inflow 0.2 l/min). The amount of water supplied to the fracture feature prior to starting the main inflow would not have been sufficient to have done more that initiate hydration in the clay surrounding this feature but provided some initial hydration. The rear-most inflow points simulated two independent flow features that were progressing along the tunnel perimeter from some distance up-tunnel. This simulated water moving down-tunnel and into a newly (120 h previously) backfilled region where the only source of water was the small seeping fracture that intersected the tunnel. The mock-up begins to monitor the interactions that begin as these flow features approach the fracture.

In Test 3 the pressures required for water to be injected into the left and right rear regions of the chamber was monitored, as was the eventual outflow of water and eroded clay materials at the downstream face of the backfilled volume.

Test 3 showed behavior different from all previous 1/12th and ½-scale tests completed at Äspö. It required more than 150 hours for water to move from the rear of the chamber to the downstream face, much longer than previously observed for any system. In total more than 1,668 l was input into chamber before flow past the fracture feature began at ~139 hr. In total this test entrained ~2,641 l of the 3,228 l input (~81.8%), the highest proportion observed prior to the conduct of Test 4. This indicates that with only a small downstream resistance to water movement, the inflowing water will tend to fill more of the voids associated with the pellet fill before finding a pathway past the isolating feature. In addition to the high degree of water uptake, this test also exhibited the highest resistance to water inflow observed in any tests to that time and even after outflow began it had a very high rate of ongoing water uptake (~62% or 0.12 l/min). Given that there were two inflow paths this water uptake might have been ~0.06 l/min for each side of the assembly (the same rate as observed in Tests 1 and 2). Rate of uptake will of course decrease with time as the system tends towards saturation.

As can be seen in Figure 3-8 the resistance to water inflow steadily increased for both of the water entry points at the rear of the chamber. This increase continued for approximately 110 hours when the water moving along the left side reached the artificial fracture feature and pressure dropped substantially as water flowed in to fill the geotextile and begin further wetting the pellets adjacent to it. As wetting of the region around the fracture progressed (115–125 h) resistance to further inflow recovered

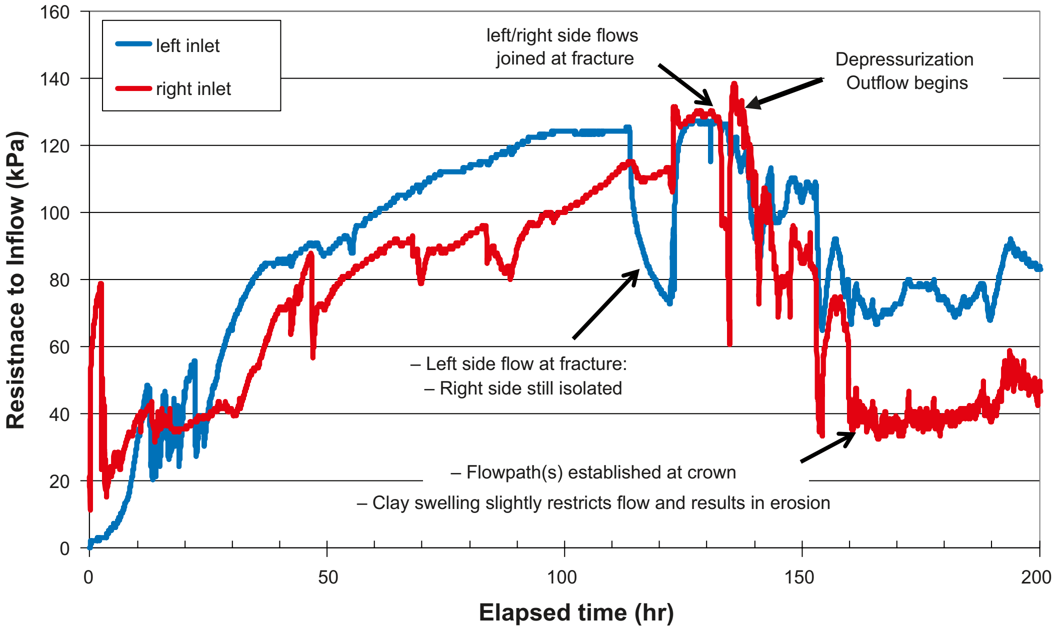


Figure 3-8. Backfill-induced resistance to water inflow in Test 3.

to previous levels. Resistance to inflow recorded for water supplied from both sources was constant at ~135 kPa until 139 h into the test when the compressed air-water mixture behind the fracture breached the remaining 1.9 m length of the backfill pellet fill at the crown of the assembly (Figure 3-9). Breakthrough by the air-water mixture was "sudden" with audible channeling of air/water past the gasket. The escape of air/water/clay mixture was as a projected stream that extended approximately 1 m past downstream face of the backfill. After decompression of the isolated region there was a gradual shift in flow path to the upper left quadrant of the assembly where flow and erosion continued for the remainder of the test.

Associated with water exiting Test 3 was a considerable quantity of pellet material (Figure 3-9). The initial decompression of the isolated volume included removal of air, water and clay with ongoing water-clay outflow for the remainder of the test. In total, approximately 100 kg of clay was removed in a 60 hour period, an average of 1.67 kg/h (or 0.397 kg/l of outflowing water). The outflow proportion at the end of the test was approximately 38% of the inflow volume and as a result the material removed represented a very high sediment load. At a total inflow of only 0.2 l/min, this was an erosion rate that was many times higher than had previously been observed for similar inflows via point sources where no gasket-like feature had been present. The development of and subsequent release of a pressurized volume in the tunnel had a very detrimental effect on the behavior of the system.

In the course of dismantling Test 3 careful note was taken of the wetting of the pellet and block materials. Figure 3-9 shows several profiles through the assembly and in the regions downstream of the fracture feature, wetting was relatively limited and largely associated with the pellet-fill immediately in contact with the chamber wall. There was only limited wetting of the blocks closest to the major flow paths. At and behind the fracture feature the water distribution was much different than was evident in the downstream regions. As can be seen in Figure 3-9 the pellets in the region of the fracture are entirely saturated with wetting extending well into the volume occupied by blocks. Behind the fracture the pellet-filled region was almost completed saturated (a few small pockets of dry material were still present) and the wetting of the blocks was very pronounced, particularly at the crown and on the left side of the assembly. With wetting of the blocks and pellets the borders between these two components became difficult to distinguish, indicating that they had begun to swell/compress to form a more homogeneous backfill in those regions.

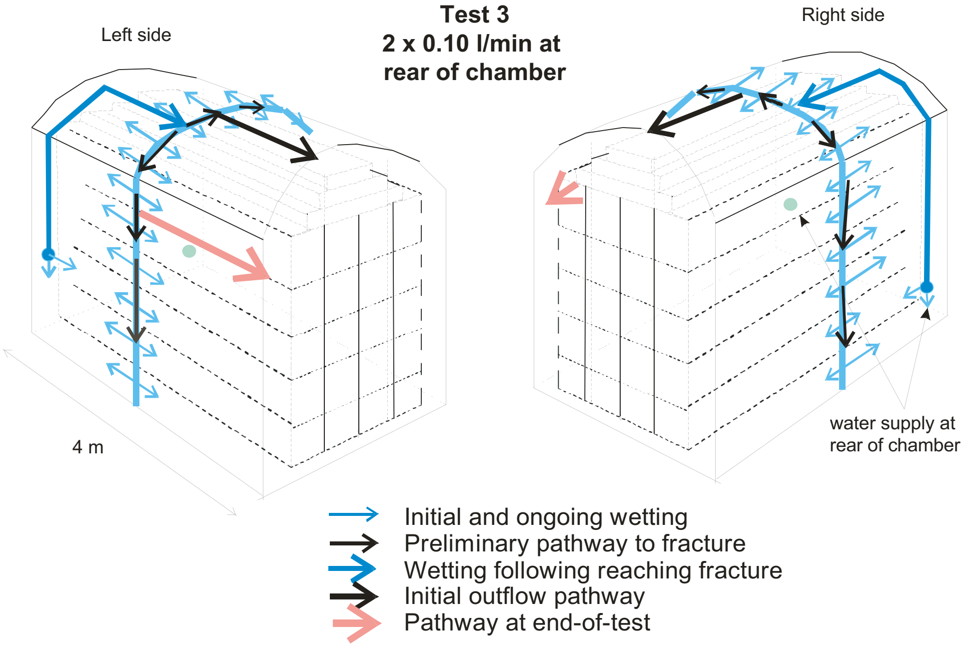
The addition of a food dye (blue coloured) to the water injected into the test during the final minutes of its operation provided confirmation of the indirect measurements and observations made in the course of test operation. The dye had only a modest uptake by the adjacent clay in the short time it was used and provided a means of visually marking the flow path(s) at the time of test termination. This dye was also non-toxic and so did not pose any health or environmental issues with regards to disposing of the waste water from the tests. As can be seen in Figure 3-10, the dye was very effective and at the end of testing the water is moving into and through the backfilled volume via a clearly defined pathway. The water moves very directly to the crown of the chamber and then almost straight to the downstream face. In Test 3 (and also in Test 4) this water movement is via a narrow feature located at the pellet-chamber wall interface. From the observations of water outflow, the evidence from the dye and inflow resistance monitoring it was possible to develop an idea of how water moved through the test, this is presented as a sketch in Figure 3-9.

3.5.2 Test 4: Water inflow into tunnel section containing two isolated pockets of backfill

Test 4 was the final test in the current study. It consisted of the same assembly geometry of blocks and pellets as was used in Test 3 (Figure 2-3) excepting that its length was extended to 5.45 m, to allow for installation of a second fracture feature at 4 m distance from the rear of the chamber. Water was supplied to each of these features at the same rate as in Test 3 (0.0025 l/min) but for a longer period (312 h versus 120 h, resulting in ~47 l of addition uptake at each fracture site) in order to assess what effect more extensive gasket features would have on subsequent hydro-mechanical behaviour. Test 4 had a considerably higher amount of water utilised in its construction (740 l versus 294 l used in Test 3). While significant it represents only an increase in the as-placed saturation of the pellet fill from ~23% to ~35%, which should not have caused a substantive change in how air or water move through this component during the early stages of testing. Test 4 was also operated for a longer time due to its longer physical length and need to establish how a series of isolated pockets would interact. At the end of wetting via the fractures, the assembly was supplied with 0.1 l/min at each of the two inlet ports at the rear of the test chamber and the system evolution was monitored.

Initial outflow at crown of test

Outflow from upper left corner

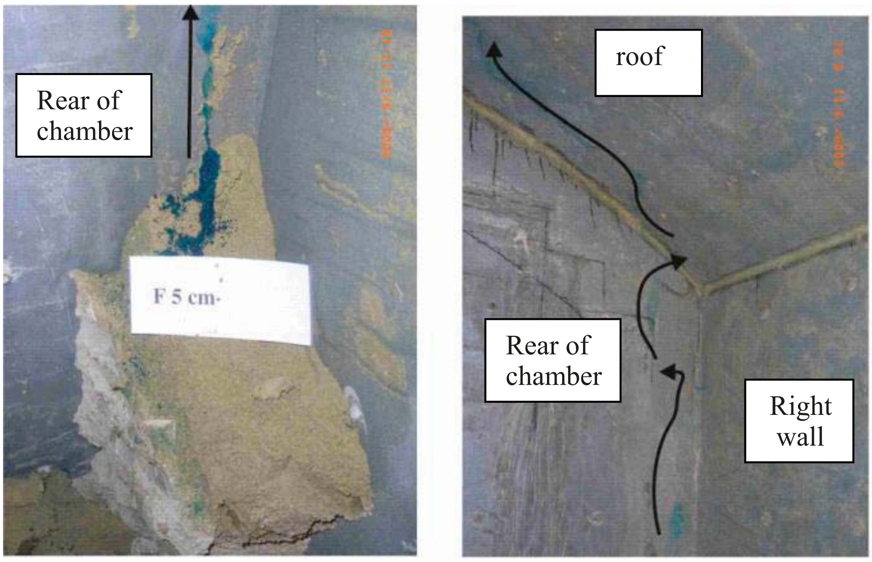


Downstream of fracture
no block wetting

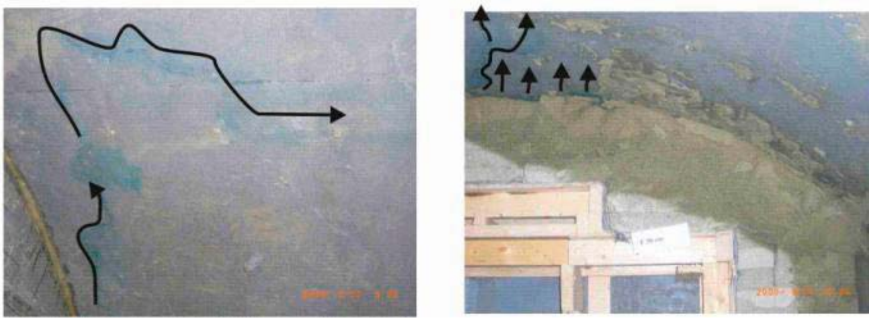
Block wetting at
fracture location

Upstream of fracture,
extensive block wetting

Figure 3-9. *Outflow locations and water distribution within Test 3. Note loss of visible interfaces as result of block hydration. Main flow paths observed were along crown and in upper left region along pellet-chamber wall contact.*



Movement of dyed water vertically to crown of chamber



Movement of dyed water along crown of chamber and out to downstream face
(arrows added to highlight path taken towards front of chamber)

Figure 3-10. *Tracing movement of water at end-of-test (Test 3). Water moved upwards almost immediately and then along the crown of the chamber towards the downstream end of the backfill.*

In the first 312 hours of Test 4's operation approximately 46.8 l of water was supplied to each of the fracture features. At the end of that time water was supplied at 0.1 l/min at each of the two inflow ports at the rear of the chamber (left and right side). Figure 3-11 shows the resistance to ongoing water input via these ports once water was supplied to the rear of the chamber. For the first 95 hours of wetting the two inlets showed fairly independent behaviour while gradually developing substantial resistance to ongoing inflow (75 and 100 kPa for right and left sides respectively). At 95 hours water travelling along the right side reached the innermost fracture feature and within a few hours the left side also reached the inner fracture and the two flow paths were combined at that point. It is possible that this water being supplied to the fracture feature was primarily responsible for rapid formation of an effective seal at the location and the substantial resistance to inflow that developed. Once the inner gasket was reached and water forced its way past this feature, water began entering the isolated zone between the two gaskets and considerable resistance to further inflow developed. The system ultimately developed approximately 185 kPa resistance to inflow and maintained that pressure for approximately 1 day before the outer gasket was breached at the crown of the assembly (at ~160 h). Figure 3-12 shows the location of the initial outflow point, the material removed as well as the results of ongoing outflow from the assembly. As was the case with Test 3, the depressurization was rapid and audible, followed essentially immediately, with discharge of substantial quantities of water and sediment at the downstream face of the backfill.

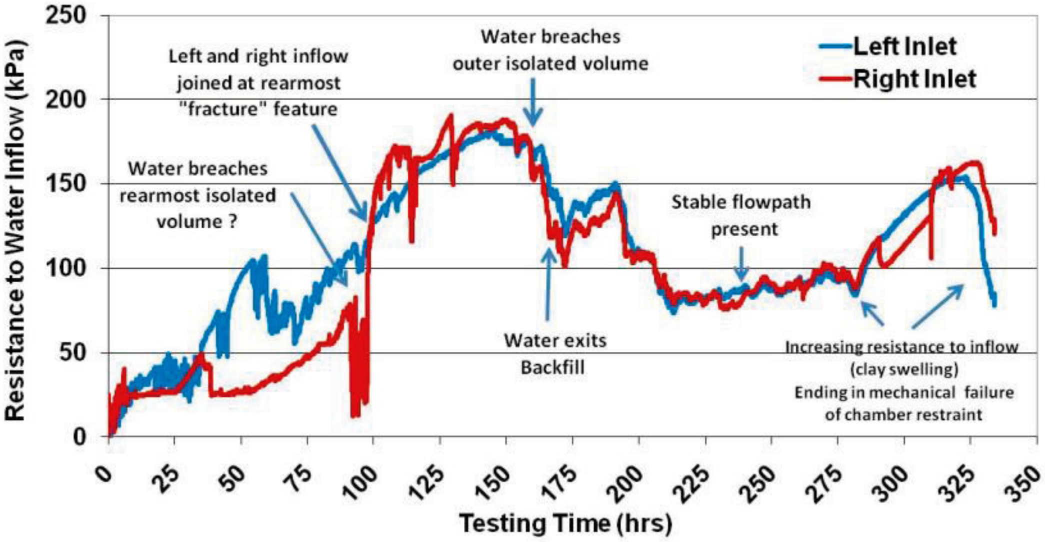


Figure 3-11. Backfill-induced resistance to water inflow in Test 4 once inflow at rear of chamber was initiated.

Outflow at crown

Clay removed by exing water

Figure 3-12. Test 4 showing location of water outflow and large quantity of clay carried out of pellet-filled regions.

The data shown in Figure 3-11 indicates that the system underwent some limited resealing at 175–190 h, but subsequent erosive action resulted in a reduction in the resistance to flow for the system. This decrease in resistance may be associated with the shifting of the outflow region from the centre to a region more to the left of the chamber crown (Figure 3-12). Between approximately 200 and 280 h the resistance to inflow remained constant at approximately 80 kPa, indicative of a fairly stable flow and either a stable or potentially reducing erosion rate.

At 289 h into the test the resistance to inflow showed a steady increase and toward the end of this time there was mechanical failure of the very robust internal formwork. Formwork failure resulted in a drop of inflow resistance as the compressive forces that were previously impeding water movement along the chamber wall-pellet interface were partially released. The increasing resistance to inflow and mechanical failure of the formwork (Figure 3-13) approximately 325 h after the start

5.1 m (near front) 4.5 m 3.9 m (outer fracture) 3.3 m

2.7 m 2.0 m (inner fracture) ~1.2 m ~0.3 m (back)

Figure 3-13. *End-of-Test Water distribution within Test 4. Photos show extensive water retention and swelling in region behind inner fracture (~2 m), including mechanical failure of internal framework at ~1.2 m, limited wetting in region between fractures (2–4 m) and essentially unaltered regions downstream of outer fracture (excepting front face of assembly, wet by exiting water).*

of water injection at the rear of the chamber can be attributed to the swelling pressure that was developing within the regions filled with clay blocks and pellets. Swelling-induced pressures would have been highest in this region as this is where water uptake had been greatest. Estimations of swelling pressures present in this and the other tests are provided in Section 4. The evolution and the interpreted pathways for water flow into and through Test 4 are shown schematically in Figure 3-14

At the time of test completion, Test 4 had lost approximately 186 kg of clay in 160 h of outflow. This works out to an average loss of 1.16 kg per hour (0.276 kg/l of outflowing water based on 35% outflow rate measured). Unfortunately due to the large quantities of material collected it was not possible to quantify changes in erosion rate during that period. Visual inspection indicated that considerable erosion was still occurring at the end of the test. In the course of dismantling this test there was no evidence of extensive localized erosion of clay, it would appear that material was removed gradually as the clay swelled into contact with the water moving along the preferential flow path.

Test 4 had approximately 94 l of water supplied directly to the fractures followed by approximately 1,950 l of water supplied to each of the inlet ports at the rear of the chamber. Prior to the start of water outflow from the chamber at 160 h, approximately 1,920 l of water was input to the system. In total some 4,000 l of water was input over the course of the test and approximately 3,200 l of this was stored within the pellet and backfill (~80%). Once outflow began, the volume retained by the assembly averaged 0.08 l/min, slightly lower than, but still comparable to what was observed for Test 3. As saturation increases it would be expected that the ability of the system to take on additional water would tend towards zero.

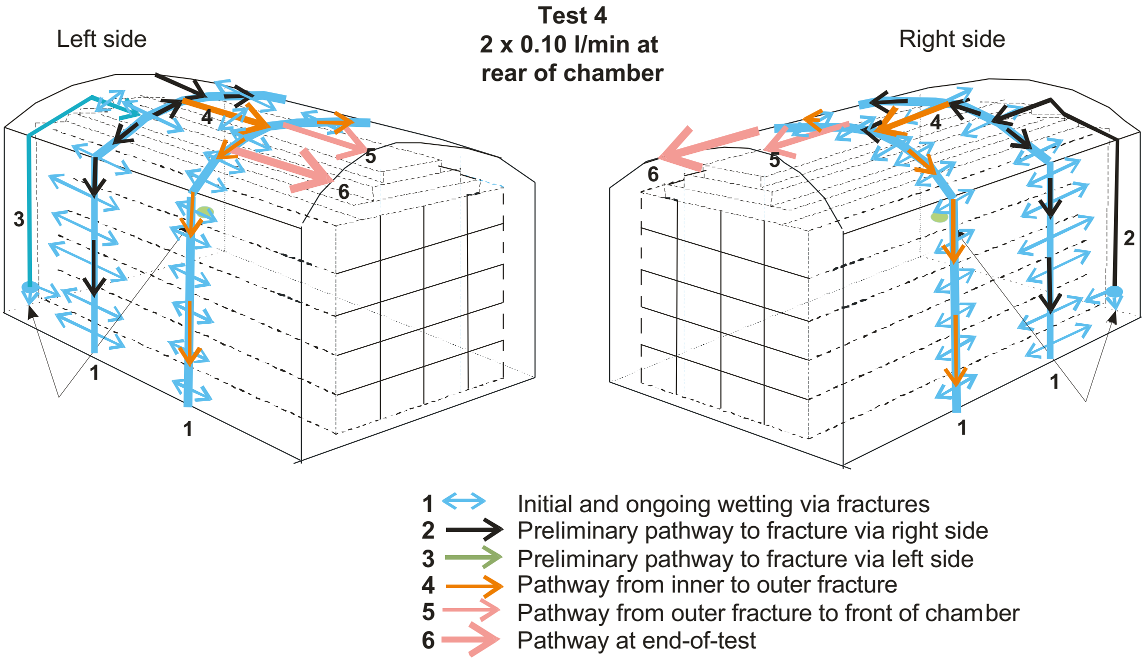


Figure 3-14. *Pathways taken by water as it moved into and through Test 4.*

The distribution of water within the backfilled simulator was consistent with the interpretations of the inflow resistance data and the observations made in Test 3. The region between the outer fracture feature and the front face of the backfilled volume showed extensive water uptake by the pellet materials, especially in proximity to the fairly extensive flow path(s) active along the crown of the chamber during the test (see Figure 3-13). The blocks in this region did not show such extensive wetting, with wetting largely associated with the regions immediately adjacent to the pellets. The pellets at the location of the outermost fracture feature were effectively saturated with some more extensive wetting of the adjacent pellets evident. Between the two fracture features there was nearly complete wetting of the pellet fill, although a few localized dry areas remained. The blocks in this region had begun to saturate from the contact with the pellets inwards towards the core of the construction but this uptake was still quite limited (Figure 3-13).

In the vicinity of the inner fracture feature, the pellet fill was effectively saturated and extensive water uptake by the clay blocks had also occurred. It was near the inner fracture feature that mechanical failure of the internal formwork associated with this test occurred. The clay adjacent to the inner fracture feature had undergone sufficient hydration to cause development of a substantial swelling pressure on the confinement (chamber wall and wooden formwork). This swelling pressure was sufficient to exceed the strength of the formwork. The result of this mechanical failure was ongoing swelling of the pellets and clay blocks into the gradually increasing volume of failed formwork. Figure 3-15 shows the extensively wetted areas where the boundary between the clay pellets and clay blocks became visually indistinguishable and no blocks could be individually identified. This is indicative of the potential for these components to swell (or compress, depending on the material) and boundaries between components to essentially disappear. The equilibration of the system will be a long-term process and there may be some differences between the ultimately achieved density of the components but this should be small when the same (or similar) clay materials are used for the manufacture of pellets and backfill pellets. Systems constructed of substantially-different components are more likely to persist in maintaining density differences over the long-term but the degree of this difference is not yet clearly established.

In the volume behind the inner fracture, the backfill and pellet fill was the wettest region of the test at the time of dismantling (Figure 3-13). This is the volume into which water was supplied throughout the test and so it had both the longest time available for saturation to progress and also was isolated for the first 90 hours of test operation, allowing approximately 1,000 l of water to be stored in this region before it was able to move beyond the innermost fracture.

Figure 3-15. *Homogenisation of clay blocks and pellets in Test 4. Left: location of formwork failure. Right: crown region behind fracture. The block-block and block-pellet contacts are not visible and considerable progress has been made towards homogenisation in these regions.*

3.5.3 Summary of results from Test 3 and Test 4

Tests 3 and 4 generated very similar results. The presence of the simulated fracture features resulted in focusing of water flow from different regions of the backfilled tunnel into a single combined flow feature. As a result the systems were able to take two low-flow features (2 × 0.1 l/min) that had little potential for erosive action on the backfilled system and combine them to form a single, highly erosive feature.

The presence of fracture features that had provided only a small quantity of water to the pellet backfill (18 and 47 l for Tests 3 and 4 respectively), caused a major change in the water retention and subsequent throughflow behaviour in the backfilled tunnel. The fracture-supplied water was apparently sufficient to begin the process of generating a gasket-like feature within the tunnel. Subsequently, when water moving along the tunnel intersected the fracture feature, hydration proceeded rapidly and within a few hours a feature was developed that, hampered the escape of air located beyond the fracture. The result was that substantial quantities of water were stored within the isolated pocket(s), speeding hydration of the backfill, but also delaying the arrival of water at the working face of the backfilled tunnel. It also resulted in generation of a volume of pressurized air in the occluded region(s). These gas pockets subsequently stepwise burst in audible and energetic manners past each of the fracture features, resulting in projection of a mixture of air, water and clay for a distance of up a few meters past the downstream face of the backfill. Once decompression was achieved the route taken by the escaping gas-water-clay mixture became a preferential pathway, along which water and clay continued to be transported.

4 Discussion

4.1 Test conditions examined and observations made

Detailed descriptions of the tests completed in this study are provided in Section 3 and the as-built conditions are provided in Table 3-2. A summary of the key as-placed materials properties and behaviours observed is provided in Table 4-1. The results contained in Table 4-1 are the basis for discussion regarding the major findings of this study, in particular the manner in which water is taken up by and flows through a section of deposition tunnel and what effect localised wetting will have on system evolution.

Table 4-1. Outflow and resistance to water inflow measured.

	Test 1	Test 2	Test 3	Test 4
Test Assembly Length (m)	3.9	3.9	3.9	5.45
Flow path length (m)	1.9	1.9	3.9	5.45
Inflow rate (l/min)	0.1	0.25	2 × 0.1	2 × 0.1
Inflow water quantity (L)	1,800	4,605	2,641	3,117
Water outflow quantity (L)	445	2,611	587	631
Outflow after breakthrough (% of inflow)	~40%	~76%	~38%	~35%
Total water retention (%)	74.2	56.7	81.8	82.5
Test duration (hrs)	300	307	269	334
Outflow start (hr)	40.4	1.5; 77	139	120; 175
Maximum inflow resistance, kPa	40	75	130	185
Average erosion rate on outflow start (kg/h)	~0	0.13	1.66*	1.16*
Average erosion rate per l of outflow(kg/l)	~0	0.011	0.397	0.276

* Much of eroded material was expelled during period immediately after breakthrough.
Initial as-received pellet gravimetric water content = 13%.
Blocks had a reported dry density of 1,650 kg/m^3 and gravimetric water content of %.

4.2 Effects of backfill composition

4.2.1 EMDD and TDS

The tests described in this report showed behaviour that was comparable to previous tests done at 1/12th and ½-scale. Specifically that flow of 0.1 l/min or less along a single flow path is unlikely to cause substantial disruption to the backfill. At higher flow rate along a single pathway erosion will occur and can be disruptive. There was a tendency for inflows entering the backfill at different locations to combine, potentially forming a feature that was much more erosive that would occur in separate flows that in total were equal to the combined feature.

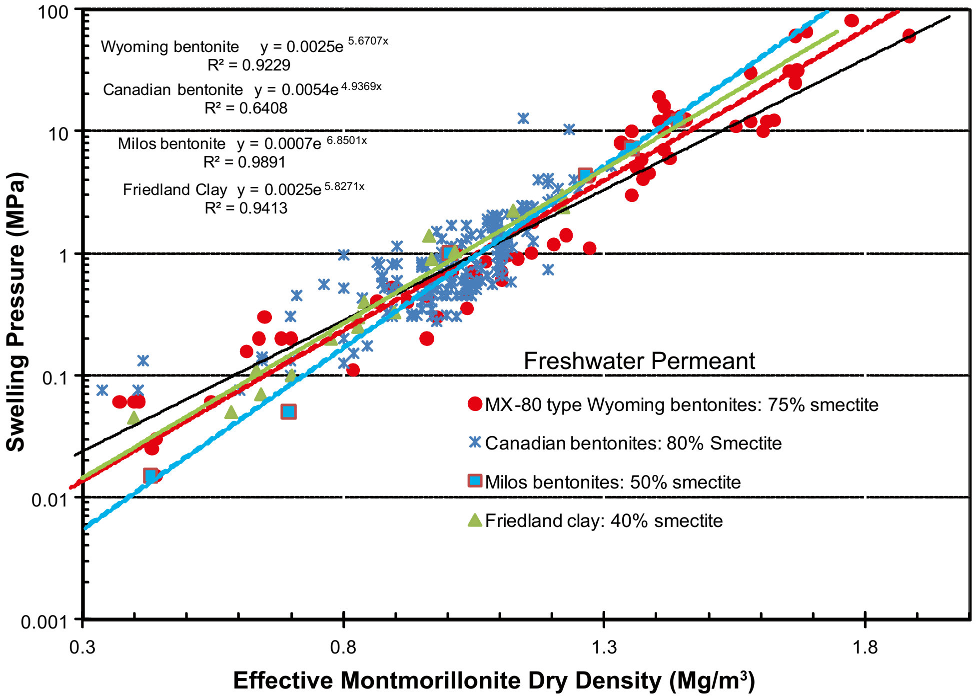
One feature that was notably different in the current tests was deformation of the front-face of the backfilled volume (Test 2) and swelling-induced failure of the internal formwork (Test 4), used to simulate the internal sections of an actual tunnel. The primary difference between previously completed and the current tests is the material used in the manufacture of the blocks. Previous tests used a lower smectite content (mixed layer clay component reported to range between ~25–45%, Table 3-1), Friedland clay that has been compacted to only 1,820 kg/m^3 dry density (2,000 kg/m^3 is reference density for blocks of this material), while the tests described in this report used a bentonite having ~50–60% (and perhaps as high as 70%) smectite (Milos B, Table 3-1) compacted to a dry density of 1,650 kg/m^3. The net result of these changes is a slightly higher average Effective Montmorillonite Dry Density (EMDD) for the Milos B blocks installed in these tests (1,200 kg/m^3) relative to the Friedland blocks used previously (1,140 kg/m^3). Table 4-2 summarises the density conditions and compares them to a ½-scale test completed previously (Dixon et al. 2008b).

As has been noted previously, the Friedland materials examined in previous studies (Dixon et al. 2008b) were actually of inferior density relative to what is achievable (1,820 versus 2,000 kg/m^3). The result of this is that the block fill used in previous tests will develop a slightly lower swelling pressure than would be present for higher density materials. It was found that for the range of density examined in laboratory tests so far completed, the mixed layer clay component in the Friedland clay behaved as a smectite. The Friedland material produced results that are comparable to those where the swelling clay content was montmorillonitic. At lower densities it is likely that this comparable swelling pressure behaviour would not persist since effects such as free-swell capacity, surface charge and other mineralogically-determined properties begin to play a larger role in terms of material behaviour.

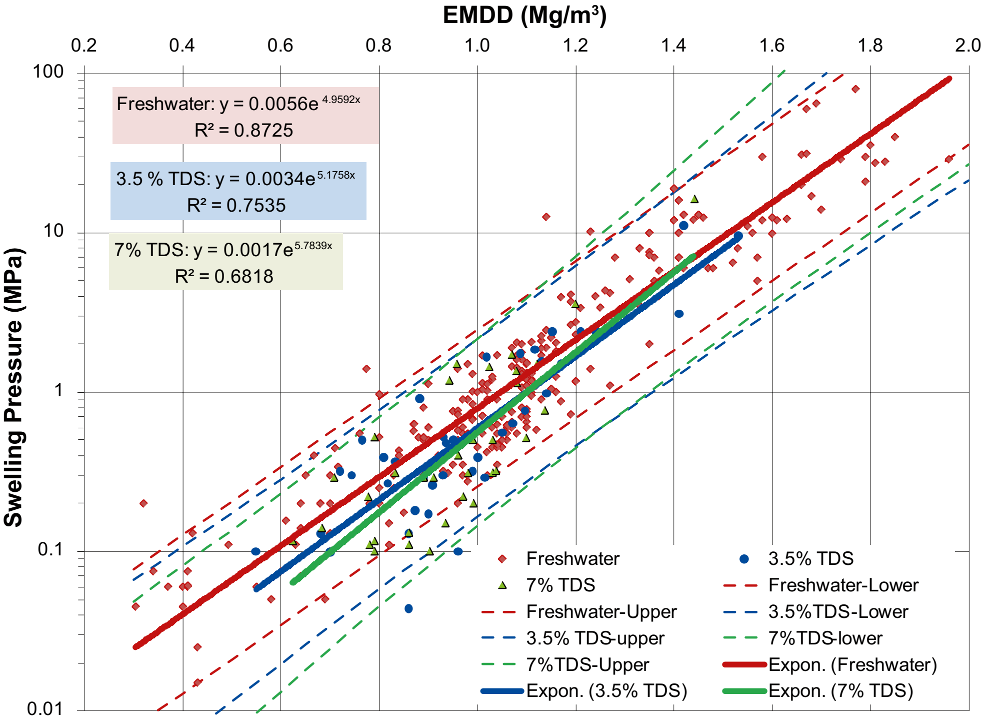
In terms of comparison of the results of the current test series to previous ones (Dixon et al. 2008b) where Friedland materials were used, the use of 2,000 kg/m^3 Friedland clay blocks would have increased the EMDD of the block component to ~ 1,446 kg/m^3 (as opposed to the ~1,140 kg/m^3 present in the lower-density blocks actually used). This would have resulted in swelling pressures higher than those predicted for the Milos B clay (if backfill equilibration based on a uniform EMDD is assumed).

As swelling pressure is related to density of the system and in particular the density of the swelling clay component it is possible to estimate the swelling pressure that the backfill will develop if the clay mineralogy is known. This assumes that ultimately full density equilibration occurs between the pellets and the clay blocks. The parameter developed to accommodate differences in smectite content and provide predictions of swelling pressure that can be developed is the Effective Montmorillonite Dry Density (EMDD) developed from relationships originally presented by Dixon (2000) and is presented in Figure 4-1 and is provided in Equation 1. EMDD allows prediction of the swelling pressure developed by and saturated hydraulic conductivity of smectite-rich materials based on the density of the swelling clay component (non-swelling materials are considered as inert filler and their mass and volume are excluded from density calculations).

Data collected from literature (Johannesson and Nilsson 2006, Sandén et al. 2008, Johannesson 2008, Johannesson et al. 2010, Karnland 1997, Karnland et al. 2006, Dixon 2000, Dixon et al. 1996, Oscarson et al. 1990), have also been used to develop empirical relationships between EMDD and swelling pressure for materials under a variety of TDS compositions (see Figure 4.1). In Equation 2 through Equation 5 the empirical relationships derived from these literature values for groundwater conditions having 0, 3.5 and 7% TDS are provided. There is a clear trend towards decreasing swelling pressure with increasing TDS. Much of the scatter observed in the data presented in Figure 4-1 can be attributed to uncertainties regarding the smectite content in the specimens tested. Smectite content can vary considerably between batches of clay bearing the same trade name and mineralogical assessments do not provide exact measures of smectite content. The data presented also represents a wide range of materials tested over several decades and so there will have been some variation in swelling clay content in products sourced over such a long time period, even if it is marketed as the same material. There may also be some differences in the measurements resulting from different testing techniques, again resulting in a degree of data scatter. In laboratory tests where exactly the same material and technique was used for freshwater and saline groundwater swelling pressure tests, the decrease in swelling pressure can be clearly observed (e.g. Karnland et al. 2006, Johannesson et al. 2010). By collecting as much data for a range of smectite-rich clays tested under a range of TDS conditions, the EMDD parameter can be used to plot the existing data and generate generic relationships between swelling pressure developed for various clay materials and TDS conditions (see Figure 4-1(b)). The equations below provide a means of estimating what swelling pressure could be expected to develop in a swelling clay soil under a variety of groundwater TDS conditions. As can be seen in Figure 4-1b there is considerable scatter in the literature data and so the equations should only be used for estimation purposes.



(a) EMDD – Swelling pressure developed by smectite-rich clays showing how behaviour of a wide range of smectite-rich clays can be normalized



(b) Effect of salinity (TDS) on swelling pressure in smectite-rich clays

Figure 4-1. *Normalization of swelling pressure based on EMDD parameter (Data used in graphs includes values reported by Johannesson and Nilsson (2006), Sandén et al. (2008), Johannesson (2008), Johannesson et al. (2010), Karnland (1997), Karnland et al. (2006), Dixon (2000), Dixon et al. (1996) and Oscarson et al. (1990)).*

Effective Montmorillonite Dry Density (EMDD) is defined as:

$$\text{EMDD} = (m_T - m_{ns}) / (1 - m_{ns}/G_{ns}) \quad (1)$$

$$\text{Swelling Pressure (Ps) in Fresh water} = 0.0056e^{4.9592(\text{EMDD})} \quad (2)$$

$$\text{Swelling Pressure (Ps) in 3.5\% TDS} = 0.0034e^{5.1758(\text{EMDD})} \quad (4)$$

$$\text{Swelling Pressure (Ps) in 7\% TDS} = 0.0017e^{5.7839(\text{EMDD})} \quad (5)$$

Where EMDD is expressed in $(kg/m^3)/1{,}000$ and Swelling pressure is in MPa.

Where for each unit volume: m_T = total dry mass (dry density); m_{ns} = mass of non-smectite component and G_{ns} is the unit weight of the non-smectite solids component. Note that smectite content is not the same as bentonite content; the proportion of smectite in the clay must be known in order to determine the EMDD.

4.2.2 Estimation of swelling pressure developed in half-scale tests

In the current ½-scale study, density equilibration and homogenisation had not been achieved at the time of test dismantling. The swelling pressure developed by the backfill on the steel walls of the chamber and the internal formwork in the centre of the assembly would therefore have been somewhere between that of the as-placed pellet material and a locally-equilibrated block-pellet material (Table 4-2). Over the very long term the tunnel backfill will come to a density equilibrium (not necessarily homogeneity), that will depend on the materials used. Rather than density homogeneity a stress (EMDD-based) equilibrium may develop and this is a topic of ongoing evaluation. For the purposes of the current study, it is assumed that EMDD homogeneity will ultimately be achieved.

In Table 4-2 the swelling pressures that could develop in each of the four Milos B constructions examined in this study were calculated based on the measurements of the materials installed and assuming that full system saturation and EMDD homogenization was achieved. The swelling pressures that could be developed in a fully backfilled simulator where target block and pellet installation densities were achieved is in the order of 800 to 2,480 kPa for a freshwater environment (95% limit and best fit values). It should be noted that under conditions of higher salinity (3.5–7% TDS) groundwater conditions that the swelling pressures developed would be somewhat lower (480–2,080 kPa). If the same backfill geometry is assumed with use of reference Friedland blocks and Cebogel pellets the swelling pressures that could develop range from 1,310–4,080 kPa for freshwater to 840–3,700 kPa for 3.5–7% TDS groundwater conditions. These values are well in excess of the minimum targets anticipated for deposition tunnel backfill. They also represent pressures well in excess of the design limits for the ½-scale chamber, highlighting why a fully-backfilled mock-up was not used and why the lower-strength wooden formwork installed was important to the safe operation of this facility.

Based on existing knowledge regarding the materials installed in the ½-scale simulator it is also possible to estimate the hydraulic conductivity of each of the tests once full water saturation is achieved and the backfill has completely equilibrated. This provides a quick check on the potential long-term suitability of the backfill options with respect to the performance specifications established. Specifically, that the backfill act as a diffusion-dominated barrier to water movement (Section 1), which translates to a hydraulic conductivity (K) in the order of 10^{-10} m/s.

From available literature on the role of EMDD and groundwater TDS it is possible to estimate the saturated hydraulic conductivity of the deposition tunnel backfill installed in the ½-scale simulations as well as a system that was constructed using target block and pellet installed densities (Table 4-2). In all the ½-scale installations, the K of the fully-saturated and EMDD-homogenised Milos B backfill would meet the target set of the deposition tunnel backfill under all of the groundwater conditions currently envisioned by SKB and Posiva. In the case of the previously completed low-density Friedland clay block – Cebogel pellet backfill examined in previous mock-ups, the K calculated for that system is still nearly an order of magnitude less than the 10^{-10} m/s minimum target, even if the TDS conditions were 7%. As is the case for swelling pressure, when estimating the hydraulic conductivity of the backfill, it should be noted that literature data contains considerable scatter and so best-fit values were also bounded by the much more conservative 95% confidence limit values in Table 4-2. It is possible that a comprehensive review and compilation of literature data describing the hydraulic conductivity could aid in more tightly defining the relationships between EMDD, K and groundwater TDS but it is unlikely that this would change the general conclusion regarding the suitability of these materials for use in deposition tunnel backfilling.

Table 4-2. Backfill density and swelling pressures in ½-scale tests.

	Test 1: 6 l/hr	**Test 2: 15 l/h**	**Test 3: 2×6 l/hr**	**Test 4 2×6 l/hr**	**Previous tests using low density Friedland blocks***	**Milos B backfill using 1,000 kg/m^3 pellet fill**	**Friedland backfill using 2,000 kg/m^3 blocks****
Length (m)	3.9	3.9	3.9	5.45	3.9	3.9	3.9
Dry density Pellet fill kg/m^3	910	920	840	880	~1,000	1,000	1,000
EMDD of pellets$^+$ kg/m^3	638	646	581	613	712	615	712
Block					Low-density		
Dry density	1,650	1,650	1,650	1,650	1,820	1,650	2,000
EMDD*	1,200	1,200	1,200	1,200	1,140	1,200	1,446
Peak inflow resistance, kPa	40	75	130	185	<100 (typ. ~50)	-------	------
Conditions in ½-scale tunnel simulator if no central spacer were used and EMDD homogeneity achieved							
Avg. dry density	1,513	1,514	1,531	1,540	1,677	1,547	1,841
EMDD	1,194	1,194	1,212	1,222	973	1,229	1,329
Swelling pressure, kPa^{++}							
~ 1% TDS	**670–2,090**	**670–2,090**	**730–2,280**	**770–2,400**	**200–700**	**800–2,480**	**1,310–4,080**
~ 3.5–7% TDS	**390–1,700**	**390–1,700**	**430–1,880**	**460–2,000**	**130–500**	**480–2,080**	**840–3,700**
Hydraulic conductivity^{+++}							
~1% TDS	$<1 \times 10^{-12}$	$<1 \times 10^{-12}$	$<1 \times 10^{-12}$	$<1 \times 10^{-12}$	$<4 \times 10^{-12}$	$<1 \times 10^{-12}$	$<1 \times 10^{-12}$
3.5–7% TDS	$<4 \times 10^{-12}$	$<4 \times 10^{-12}$	$<4 \times 10^{-12}$	$<4 \times 10^{-12}$	$<1 \times 10^{-11}$	$<1 \times 10^{-12}$	$<1 \times 10^{-12}$

* Data for tests using 1,820 kg/m^3 Friedland clay blocks rather than the targeted dry density of 2,000 kg/m^3. Friedland clay (~40% smectite) and Cebogel QSE pellets (~80% smectite), see Table 3-1.

** If Friedland clay blocks were 2,000 kg/m^3 dry density.

$^+$ Milos B bentonite used to manufacture clay blocks to dry density of 1,650 kg/m^3 and also to manufacture clay pellets used in Tests 1–4. Simulator test as-placed density for pellet fill is assumed for calculations (see Table 3-1 for mineralogical data, 60% smectite assumed).

$^{++}$ Fully-saturated and EMDD homogeneous backfill in simulator, 82–86% block placement, values provided are for lower bounds (95% confidence limit) and best fit equation.

$^{+++}$ Fully-saturated and EMDD homogenous backfill in simulator, 82–86% block placement, values provided are for upper (higher *K*) bounds of data (95% confidence limit).

4.3 Erosion of backfill

Erosion of the pellet fill materials proved problematic for the two tests that examined the effects of isolated volumes within a backfilled tunnel. While water movement along the tunnel to the downstream face of the backfilled volume was delayed by the presence of locally hydrated regions (formed as the result of intersecting, water-bearing fractures), these features tended to cause development of volumes of pressurized air as the isolated volumes took on water. These pressurized volumes ultimately breached the constraining clay and the result was sudden expulsion of air, water and clay at the downstream face of the backfill. The loss of confinement caused by this breach resulted in development of an ongoing flow path along the tunnel and this feature was capable of removing considerable amounts of pellet fill material.

The tests presented in this document represented mock-ups of tunnel conditions where there is little or no restriction to water movement from the tunnel section to the open, downstream face of the chamber (steel mesh at downstream face). The result is that exiting water has the potential to pickup material as it flows down the face of the clay, potentially increasing the amount of material removed.

It should also be noted that the tests discussed in this report were done using simulated Äspö water (TDS 1%). This is the lowest salinity used in any of the large-scale tests and so they should have the highest swelling potential and greatest resistance to erosion for a given as-placed density. In higher salinity conditions it might be expected that erosion would be higher, however the lower swelling pressure that would develop under these conditions might mean a lower potential for isolated sections to develop high gas pressures (lower confinement may allow for easier breaching of confining materials). These issues need to be clarified through further studies done at scales representative of field conditions.

Although substantial material was removed in Tests 3 and 4, there was no evidence that the water pumped through the simulator was moving through the pellets and into the blocks via discrete flow paths. All of the data and observations indicate that water supplied at rates of <0.2 l/min was either moving along the pellet-chamber contact as discrete flow or into the block-filled regions as the result of suction-driven processes. It would therefore be expected that for field situations where flow was in this order, erosion will be associated with fairly uniform removal of pellet-materials at the perimeter of the tunnel. The quantities of material lost in the course of completing Tests 3 and 4 highlight the need to ensure that there are no unduly long interruptions to backfilling operations and that means be developed to handle any exiting water without compromising ongoing backfilling operations or backfill integrity. Minimizing the rate at which water enters the backfill during the pre-saturation period will greatly simplify repository backfilling operations and in some locations pre- or post-construction remediation of highly conductive geological features may be necessary.

Work done previously by Sandén et al. (2008) determined that the erosion of bentonite materials is greatly increased if the percolating fluid has a high TDS. The exact relationship between erosion rate and sensitivity to salinity or smectite content is not yet clear but for a given material increasing groundwater salinity results in increasing susceptibility to erosion. This behaviour was observed in ¼-scale tests completed by Riikonnen (2009) and continues to be observed in ¼-scale tests being conducted as part of Posiva's BACEKO testing program. These results highlight the importance of knowing and monitoring the groundwater conditions at the repository site and the need to develop means of minimizing the effects of groundwater salinity on the stability of the backfill.

4.4 Effects of fracture features on water movement

The four tests completed all examined the effects of fracture features that intersect a backfilled tunnel. The first two tests examined water entering the backfilled tunnel via a simulated fracture and how it would subsequently move towards the open end of a tunnel. Both of these tests showed the tendency for the pellet materials to absorb water quite uniformly from such hydraulic features. As hydration progressed in the vicinity of the fracture, water was being drawn into the block materials adjacent to the pellets and fractures, again in a very uniform manner and with no evidence of any mechanical disruption beyond swelling of the blocks to locally compress the pellet materials being observed. The resistance to water entry into the chamber gradually increased since the clay could not take on water at the rate it was being supplied. The result was the development of a series of small channel flows at the pellet-chamber boundary. These features lasted for various durations as incoming water continuously sought the path of least resistance into the chamber. The result was a heterogeneous wetting pattern in the pellet fill. Ultimately, the water entering the chamber was able to develop a flow path that allowed it to move past the backfill and exit at the downstream face.

In comparing the rate of entry and throughflow over the course of the tests it was observed that the water uptake by the backfill was fairly consistent at 0.06 l/min, with excess passing through and out of the chamber via the subsequently developed flow path(s). This rate of uptake is comparable to that observed as being the natural limit for uptake by saturating backfill in previous ½-scale tests and that at inflow rates in the order of 0.1 l/min any water exiting the chamber carried essentially no eroded material with it. From these observations it would seem that the quantity of inflow that can be accommodated by an unsealed backfilled section of tunnel is limited and there exists the potential for potentially disruption outflow from the working face of the backfill if installation is not done in a timely manner.

The last two tests done in this study examined the effect of fracture-induced volumes of saturated material on movement of water into isolated, previously dry volumes of tunnel. The specifics for each test are presented in Section 3 but it was noted that the simulated fracture features acted as hydraulic junctions where water moving along a tunnel could combine into a single hydraulic feature that carried the sum of the flows. The result of combining smaller flow features, that were by themselves non-erosive into a single, larger flow feature was generation of erosive action by the water. Outgassing of the isolated volumes to the still open sections of the deposition tunnel were energetic and resulted in development of highly erosive activity in perimeter regions of the tunnel. Again, as was observed with previous ½-scale tests, water flow seems to be confined to the tunnel perimeter, although water continued to be gradually drawn into adjacent pellet and block materials.

From the tests conducted in the ½-scale tunnel simulator it would appear that there exists a potential for disruptive water flow through or past already backfilled portions of a deposition tunnel, especially if backfilling operations were interrupted for several days. The presence of multiple small water flow features that are not in themselves problematic can become an issue if they intersect with rock fracture features that intersect the tunnel perimeter, the result being a combination of the small features into a single larger, and more disruptive flow feature. It might be possible to deal with such situations by installation of a removable artificial drainage system, such as proposed for the KBS-3H deposition concept or discussed in Section 4.5.4 but this will need to be demonstrated as being a workable solution.

4.5 Comparison to previous water uptake simulations

4.5.1 Calculated equilibrium conditions: constraints applied

All of the tests described in the current and previous ½-scale studies simulated a block filling efficiency of 80–85%, representative of what can likely be achieved in a repository environment. There was a discernible reduction in the density to which the pellets were placed in this study 820–920 kg/m^3 versus the ~1,000 kg/m^3 achieved in previous ½-scale tests. If the dry density to which the pellet fill will be placed in a repository is required to be >1,000 kg/m^3, development of methods that will be capable of consistently achieving this density are needed. In order to provide conservative (lowest likely) swelling pressure values, the Milos B bentonite used to manufacture the blocks and pellets was assumed to be at the lower end of its reported smectite content (60%). The Milos B material is also a calcium-bentonite means that its free-swell capacity is more limited and this may be important in regions where the as-placed density is very low. Previous tests used Friedland clay blocks of 1,820 kg/m^3 dry density and very low (estimated <40%) smectite content. As a result those Friedland blocks have slightly lower swelling potential than Milos B materials. Overall behaviour in the Friedland-Cebogel tests would in part be compensated for by the high-quality (80% smectite) sodium-activated Cebogel QSE pellets but the volume ratio of blocks to pellets meant that it was the composition of the blocks has the greatest effect on the EMDD of an equilibrated backfill. The combination of low-density Friedland and Cebogel materials therefore has a more limited potential to develop swelling pressure.

In previous ½-scale tests the as-placed pellet dry density was 950–1,080 kg/m^3 using Cebogel QSE bentonite (80% smectite) rather than what was achieved using the Milos B (~50% smectite) material used in the current studies. In order to compare the potential for development of swelling pressures and the observed hydraulic behaviour of the current tests and those completed previously the results of a series of calculations are provided in Table 4-1.

4.5.2 Evaluation of anticipated behaviour

The differences between an equilibrated Friedland-Cebogel and Milos-B tunnel backfills examined in this and previous studies (Dixon et al. 2008a, b), is evidenced in the swelling pressure and hydraulic conductivity that would be expected in density-equilibrated systems. The previously completed Friedland-Cebogel system was constructed using low-density blocks (1,820 rather than the 2,000 kg/m^3 blocks originally specified). Backfilling a tunnel to an 85% tunnel filling efficiency using such a block material would result in a system that should exhibit a saturated and density-equilibrated swelling pressure in excess of 200 kPa (lower 95% bound on data) in a 1% TDS groundwater environment and would exceed ~130 kPa if the groundwater TDS was 3.5% (again lower 95% limit). In this environment K would be <10^{-12} m/s for any of the conditions examined.

A similarly installed backfill composed entirely of clay blocks and pellets constructed using Milos B would develop a swelling pressure in excess of 800 kPa for a TDS of 1% and in excess of 480 kPa if the TDS was 3.5%. The hydraulic conductivity will be <10^{-12} m/s for Milos B backfill under these TDS conditions. It should be noted that these values are based on a body of data that contains considerable scatter and so should be taken for general scoping purposes only.

In the tests conducted at Äspö, both the Friedland-Cebogel and Milos B backfill systems had their initial hydraulic behaviour dominated by the pellet fill component and showed similar patterns of water movement and erosion susceptibility under conditions where flow along a single flow feature exceeded ~0.2 l/min. This is important given that the Friedland clay blocks used in previous tests were of inferior quality due to a manufacturing error. The similarity of the water movement past the pellet-filled regions in all of the ½-scale tests indicates that the block density was not likely to affect the short-term behaviour of the system. It also appears that restricting air escape from and subsequent venting of isolated and pressurized volumes of unsaturated backfill to the front face of an open tunnel section can generate substantial disruption at the backfill-rock interface. Subsequent to venting at the downstream face much of the water entering the tunnel can travel freely to the downstream face along the flow path generated by the venting air/water and can result in erosion of backfill.

While the data generated in this study should only be used for indicative purposes since the ½-scale chamber does not entirely simulate field conditions, there are some general results that can be drawn with respect to time between backfill installation and development of potential water issues, (e.g. water exiting downstream face, gas venting, clay erosion and deformation of downstream face of backfill).

For the geometry and boundary conditions in the ½-scale simulator the following suggestions/guidelines can be suggested:

- If a 5 m section of dry tunnel is backfilled and there is no water entering the backfill from previously backfilled tunnel volumes, for a flow feature being supplied 0.1 or 0.25 l/min, water should not pass through the newly backfilled section for approximately 2 to 7 days (Table 4-1), which should allow for backfilling operations of ~5 m/d to stay ahead of any seepage. The presence of higher flow rates will reduce the time needed for outflow to occur and will cause considerable erosion of pellet materials once outflow develops.
- The presence of intersecting fracture features can result in small flow features combining to form a larger, more disruptive flow.
- The nature of the supply of water to the tunnel will greatly affect the time to breakthrough and subsequent erosion. The presence of dispersed seepage-type features will allow for greater water uptake by the system before there is sufficient resistance to further uptake to result in development of discrete flow features. This will extend the time before downstream exit of water becomes a potential issue.
- The potential for water exiting the downstream face of a backfilled region to cause disruption to the backfill is directly related to how long this flow is allowed to continue to flow down the face of the backfill and the manner in which the flow path has been formed (simple water seepage, or disruptive gas-water eruption from the downstream face). Additionally the distance that the water travels will affect the short-term flow behaviour since the gradual process of water absorption of the central block-filled region will gradually reduce the amount of water available for flow along the flow feature. Over the longer-term this will not be as important and clay swelling will tend to try and close open flow paths.
- The use of some form of gas-venting and water collection system that can be removed as backfilling progresses might be useful in avoiding gas eruption and development of disruptive flow features.

4.5.3 Limitations of results

As with any artificial simulation of a natural environment, there are parameters present that are not entirely representative. However in the case of the current set of tests these are generally limited to the nature of the chamber wall – backfill pellet interface. In a field situation the rock walls will be much more irregular and less-smooth than are present in the ½-scale simulator. The presence of a rough-surfaced and potentially locally higher permeability rock in contact with the backfill pellets are likely to at least initially cause a more dispersed supply of water to the pellets than was the case in the ½-scale simulations. The result should be a more uniform water uptake by the backfill and hence a longer time before inflow results in outflow at the downstream face of the tunnel.

The simulator also had a limited length (<5.45 m) relative to what might be expected in a deposition tunnel, but was close to the length of tunnel that would be backfilled in a day. This should therefore simulate conditions that might develop in the regions closest to an open backfill tunnel. This might be conservative (interactions further into tunnel may result in slower water movement due to development of swelling pressure and multiple isolated sections within the tunnel) or non-conservative (combining of inflows from a longer length of tunnel into large flow features, generation and depressurization of long lengths of tunnel with higher compressed air volumes, potentially causing multiple venting and greater disruption of backfill). The simulator tests have however allowed for identification and to some degree quantification of the potential interactions and their significance to backfill performance. Ultimately the effects of water inflow on backfill in a deposition tunnel will need to be evaluated in a field tests where a considerable length of tunnel is backfilled and water influx is well characterised prior to backfilling.

The simulator tests done in the current series have only used low salinity (1% TDS) groundwater as the inflowing fluid which is of relevance to the SKB repository proposed for Forsmark or in situations where dilution of the local groundwater occurs during repository operations. In some situations (e.g. Olkiluoto in Finland) the TDS of the local groundwater is expected to be higher (3.5%) than for the Forsmark site. As a result, the potential for disruption of the backfill increases due to lower swelling pressure generation in saturated regions and higher potential for erosion of clay in unconfined and unsaturated regions. A very extensive body of data related to the role of TDS on swelling pressure and hydraulic conductivity of saturated swelling clays exists, but much is scattered throughout the literature. It would be useful to compile this into a comprehensive listing of the results for a range of materials, including those currently being considered as sealing system components by SKB and Posiva. This would allow for development of a more definitive set of numerical relationships for use in predicting the swelling pressure and hydraulic conductivity of various backfilling options under a wide range of groundwater conditions once saturation is achieved. This is of importance in terms of the operational period of a repository as individual deposition tunnels may achieve effective saturation while operations are ongoing in adjacent or nearby tunnels, thereby influencing movement of entrapped air and groundwater in the repository. Such data are also valuable in terms of defining materials options that would meet the longer-term (saturated) behavioural requirements for the deposition tunnel backfill (hydraulic conductivity and swelling pressure). The behaviour observed in these controlled-environment conditions should also be compared to those monitored in large-scale simulations under natural rock and wetting conditions.

4.5.4 Venting of trapped air in a deposition tunnel

As noted above, the final two tests of this study examined what would happen in a section of deposition tunnel where an unsaturated volume of backfilled tunnel were isolated by localised water uptake. Subsequent to development of such a dry pocket of backfill there may, as the result of continuing water uptake, or influx of water from an adjacent volume of tunnel be development of a pressurized pocket of trapped air. With ongoing water entry into the occluded volume will come increasing gas pressure. This air will seek to find an escape to a lower pressure environment (adjacent unsaturated pocket or downstream face of still open (or closed) deposition tunnel. The venting of such occluded gas volumes was observed in the tests completed in this study and occurred as rapid breakthroughs, carrying with it both clay and water. In the tests completed in this study, the pathway for such decompression was along the chamber-pellet interface. This location subsequently became the pathway along which water moved until it exited the chamber.

Sequential breaching of adjacent isolated pockets was observed in the study and ultimately gas reached an unconfined downstream face. As the majority of the readily available air in the backfill system is located in the pellet fill, that air is what is moving in the observed outgassing events. Once the outflow of water via the piping features was developed there was little additional evidence of more outgassing since the water was moved directly out of the system rather than compressing any remaining air.

The mock-up tests indicated that the venting of air from an isolated section of tunnel where the water could be pressurized to 1 MPa (pump capacity in mock-up) occurred at pressures much below that limit (<200 kPa). This provides some indication that a tunnel that has substantial water inflow will not see full hydrostatic pressures developed within it, but this has yet to be confirmed under repository conditions. Should this process be a concern in a deposition tunnel where backfilling is ongoing there may be the need for a deairing vent in the backfill that can be removed prior to tunnel closure or construction of mechanical bulkheads within the tunnel that will mitigate this process. The installation of a deairing system might also allow for bleeding out of inflowing water from high conductivity features in a manner that will limit disruption of the backfill during tunnel operations. The manner in which such a feature could be removed prior to tunnel closure will need to be developed but one idea might be use of a piping system similar to that shown below in Figure 4-2 where nested sections of pipe could provide a route for air escape.

The development of the KBS-3H concept for canister placement has invested considerable effort in developing means of artificially wetting (and deairing), the narrow gap between the supercontainer (canister-highly compacted bentonite surrounded by perforated metallic cage) and the surrounding rock mass. This same approach could be applied to the backfilled tunnels. Reports describing the DAWE (Drainage, Artificial Watering and air Evacuation) concept and use of pipes to wet and deair the deposition drift include SKB (2008) and Autio et al. (2008).

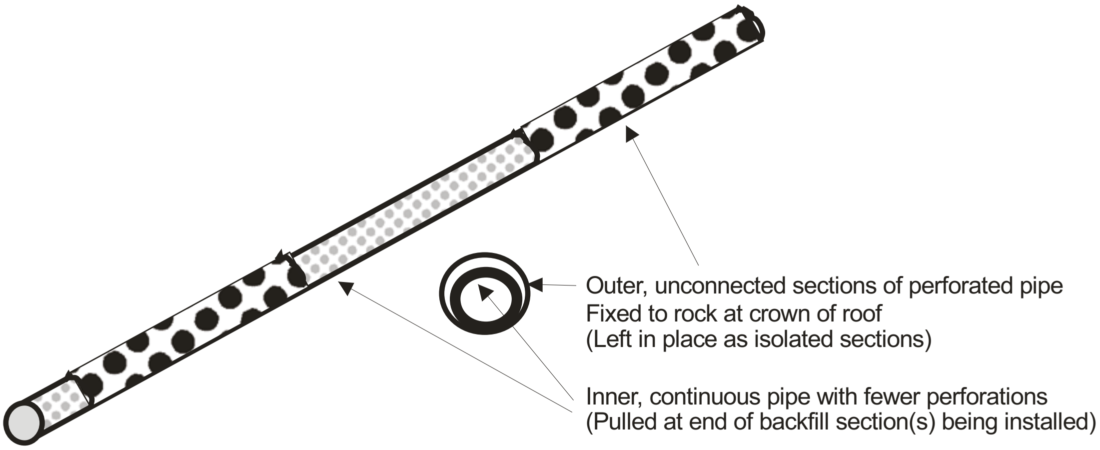


Figure 4-2. *Possible means of providing for air escape during backfill placement. Both sets of pipes are installed prior to installation of blocks or pellets.*

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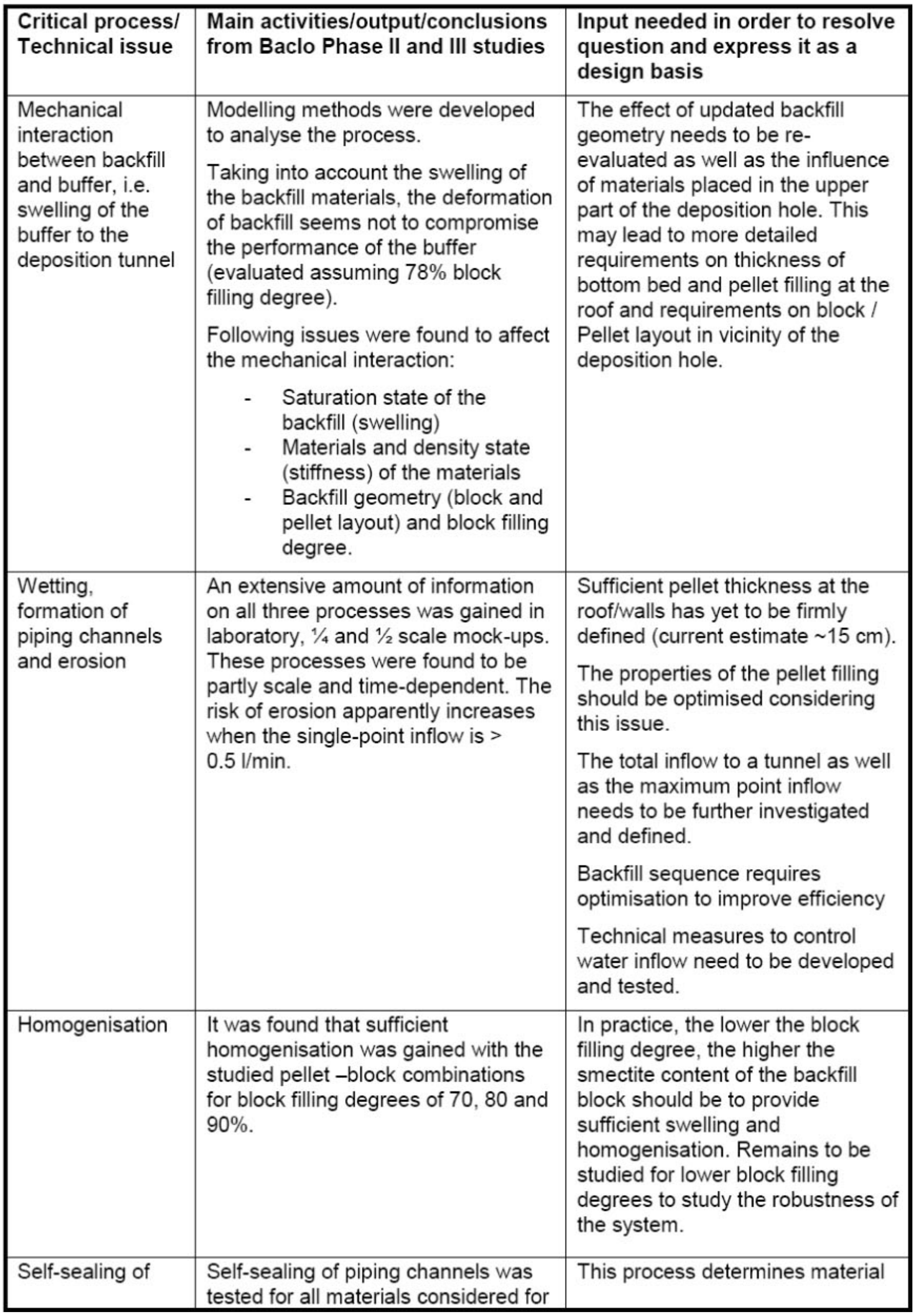
Appendix 1

Critical processes and technical issues related to design basis of deposition tunnel backfill

The following summary related to backfill design issues was provided by Keto et al. (2009b) and provides useful background to the approach taken regarding deposition tunnel backfill design.

Table A-1. Input of critical processes and technical issues on the design basis of deposition backfill.



Critical process/ Technical issue	Main activities/output/conclusions from Baclo Phase II and III studies	Input needed in order to resolve question and express it as a design basis
Mechanical interaction between backfill and buffer, i.e. swelling of the buffer to the deposition tunnel	Modelling methods were developed to analyse the process. Taking into account the swelling of the backfill materials, the deformation of backfill seems not to compromise the performance of the buffer (evaluated assuming 78% block filling degree). Following issues were found to affect the mechanical interaction: - Saturation state of the backfill (swelling) - Materials and density state (stiffness) of the materials - Backfill geometry (block and pellet layout) and block filling degree.	The effect of updated backfill geometry needs to be re-evaluated as well as the influence of materials placed in the upper part of the deposition hole. This may lead to more detailed requirements on thickness of bottom bed and pellet filling at the roof and requirements on block / Pellet layout in vicinity of the deposition hole.
Wetting, formation of piping channels and erosion	An extensive amount of information on all three processes was gained in laboratory, ¼ and ½ scale mock-ups. These processes were found to be partly scale and time-dependent. The risk of erosion apparently increases when the single-point inflow is > 0.5 l/min.	Sufficient pellet thickness at the roof/walls has yet to be firmly defined (current estimate ~15 cm). The properties of the pellet filling should be optimised considering this issue. The total inflow to a tunnel as well as the maximum point inflow needs to be further investigated and defined. Backfill sequence requires optimisation to improve efficiency Technical measures to control water inflow need to be developed and tested.
Homogenisation	It was found that sufficient homogenisation was gained with the studied pellet –block combinations for block filling degrees of 70, 80 and 90%.	In practice, the lower the block filling degree, the higher the smectite content of the backfill block should be to provide sufficient swelling and homogenisation. Remains to be studied for lower block filling degrees to study the robustness of the system.
Self-sealing of	Self-sealing of piping channels was tested for all materials considered for	This process determines material

Critical process/ Technical issue	Main activities/output/conclusions from Baclo Phase II and III studies	Input needed in order to resolve question and express it as a design basis
piping channels	backfilling. Based on the results mixture of bentonite and ballast (30:70) is not recommended as backfill material. In addition, bentonite pellets do not have sufficient self-sealing capacity in their initial dry density after installation (need to be compressed ~20% by the blocks).	selection for blocks. Sufficient smectite content needs to be defined for density states resulting from block installation efficiencies lower than 70%.
Average dry density /degree of backfilling	Analysis was made on the achievable average dry densities and the resulting material properties assuming different material alternatives. Tools to design the backfill in terms of material quality and average density have been developed. The achievable block filling degree is affected greatly by the variations in the tunnel geometry and installation method. The current estimation is that 73% of block filling degree can be achieved if the excavation overbreakage is at maximum 20%.	The lower the block filling degree the higher the smectite content of the backfill materials should be.
Installation of backfill components	Installation of backfill blocks and pellets were tested. Sufficient backfilling rate can be achieved with the static installation method under reasonably good conditions.	Static method is recommended if the required backfill rate is high but other options may be suitable under different installation rate requirements. Optimisation of the installation methods for blocks and pellets is still needed and testing under actual repository conditions is required.
Water management	The understanding of the behaviour of wetting, formation of piping channels and erosion comprises a good bases for optimising the backfill design and develop methods for handling water during backfilling.	Development and testing are still needed in order to optimise the backfill design Methods for handling water inflow during backfilling also need to be developed and demonstrated.