COMPOSITE SEAL EXPERIMENT IN AECL'S UNDERGROUND RESEARCH LABORATORY

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ABSTRACT
Concepts for deep geologic nuclear waste repositories include bulkhead seals or plugs installed at the entrances of emplacement rooms and at strategic locations in access tunnels, shafts and ramps. One potential seal type is a composite seal, in which a layer of clay-based material is placed in direct contact with a concrete plug. A composite seal, consisting of a 0.3-m-thick clay layer overlain by a 0.5-m-thick concrete plug, was installed in a 1.24-m-diameter, 5-m-long vertical borehole on the 240 m Level of the URL and hydraulically tested. This paper describes the hydraulic and mechanical performance of the composite seal over more than two years of experiment operation and describes implications of the experiment results on the design of seals for a deep geologic repository.

RÉSUMÉ
Les concepts d'entreposage géologique profond pour déchets radioactifs font appel à des cloisons ou des bouchons de scellement installés aux entrés des salles de placement et à des endroits stratégiques dans les tunnels d'accès, les puits et les rampes. Un système de scellement composite pourrait être utilisé, dans lequel une couche de matériau argileux est placée en contact direct avec un bouchon en béton. Un tel système composé d'une couche d'argile épaisse de 0,3 m recouverte par un bouchon de béton épais de 0,5 m a été installé dans un trou de forage mesurant 1.24 m de diamètre et 5 m de long au Niveau 240 m du Laboratoire de Recherche Souterrain (LRS). Ce système composite de scellement et a été soumis à des essais hydrauliques. Cet article décrit la performance hydraulique et mécanique du système sur une période d'essais de plus de deux ans. Les implications des resultants expérimentaux pour la conception de systèmes de scellement pour entreposage géologique profond sont examinées.

1 INTRODUCTION

Canada's Underground Research Laboratory (URL) is a geotechnical research and development facility constructed by Atomic Energy of Canada Ltd. (AECL) as part of the Canadian Nuclear Fuel Waste Management Program. The URL is constructed in the Lac du Bonnet granite batholith in southeastern Manitoba and provides a representative geological environment in which to conduct small- to large-scale multidisciplinary experiments. The safety of a deep geologic repository relies on the combined performance of the natural barrier (host rock) and engineered barriers (the waste form, the waste container and the repository sealing systems including buffer and backfill materials and bulkhead seals). The bulkhead seals (also called plugs) are to be installed at the entrances to emplacement rooms and at strategic locations within access tunnels and shafts (see Figure 1). Bulkhead seals restrain the swelling clay sealing materials within the emplacement rooms and isolate the closed emplacement rooms from open access galleries during the pre-closure phase of the repository. The sealing systems are designed to minimize seepage, and hence the potential for advective transport of radionuclides, along the length of the openings. The bulkhead seal itself is designed to interrupt flowpaths through the near-field rock or the backfilled tunnels. As shown in Figure 1, seals will also be used to isolate regions of high groundwater flow from the rest of the repository. A seal at the top of each shaft or ramp would be used to cap the repository

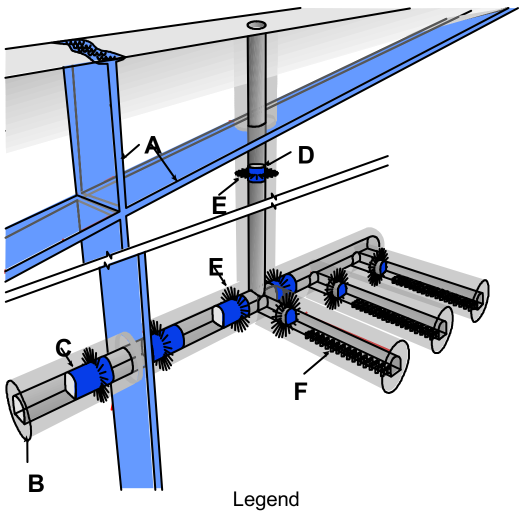

Figure 1: Potential Major Flow Pathways and Sealing Systems in a Nuclear Waste Repository

once the decision is made to close the site.

The bulkhead seals or plugs are constructed of swelling clay materials and/or concrete. Providing a layer of compacted bentonite-based material in direct contact with a concrete plug can synergistically improve the performance of the seal system. The self sealing and self healing capabilities of the compacted bentonite-based material provide an effective seal at the plug-rock interface, even if the interface between the rock and concrete plug is disrupted due to their different thermal expansion/contraction characteristics. Moreover, the development of swelling pressure and the swelling capability of the compacted bentonite-based material will assist with sealing of the excavation disturbed zone by closing circumferential fractures and penetrate into fractures exposed on the excavation surface. All the while the concrete plug rigidly confines the compacted bentonite-based material. Thus the high strength, structural rigidity aspects of the concrete and the swelling and self healing capabilities of the compacted bentonite-based material can be used synergistically in a composite seal arrangement.

Many international concepts for deep geologic disposal of radioactive waste also include bulkhead seals or plugs. Several large-scale experiments have been carried out in URLs to examine the in situ performance of bulkhead seals or plugs. These experiments include the Backfill and Plug Test, being carried out in the Äspö Hard Rock Laboratory in Sweden (Gunnarsson et al., 2001) and the Tunnel Sealing Experiment (TSX), being carried out in the Canadian URL (Martino et al., 2003). The TSX is examining the full-scale behaviour of a swelling clay and a concrete bulkhead constructed in a 3.5 m high x 4.4 m wide tunnel. The bulkheads were constructed at opposite ends of a tunnel that was hydraulically pressurized to 4 MPa and their upstream faces reached ~60°C. In order to examine the hydraulic and mechanical performance of a composite swelling clay/concrete seal and the synergism between the two component materials, the composite seal experiment (CSE) was installed in the Canadian URL. This paper describes the test arrangement and construction of the experiment and results to date.

2. CSE ARRANGEMENT AND CONSTRUCTION

The CSE was installed in a pre-existing 1.24-m-diameter, 5-m-deep borehole on the 240 Level of the URL. In this region the in situ stresses are σ_1 = 26 MPa (trend/plunge 228°/8°), σ_2 = 16.8 MPa, (135°/28°), σ_3 = 12.8 MPa (33.5°/65°). These stresses are not high enough to induce borehole wall damage from excavation. Moreover, the borehole was drilled with high-pressure water jet equipment, which also limited borehole wall damage. The 5 m depth of the borehole allowed the composite seal to be placed below the depth of the room excavation damage zone (EDZ). The arrangement of the CSE is shown in Figure 2.

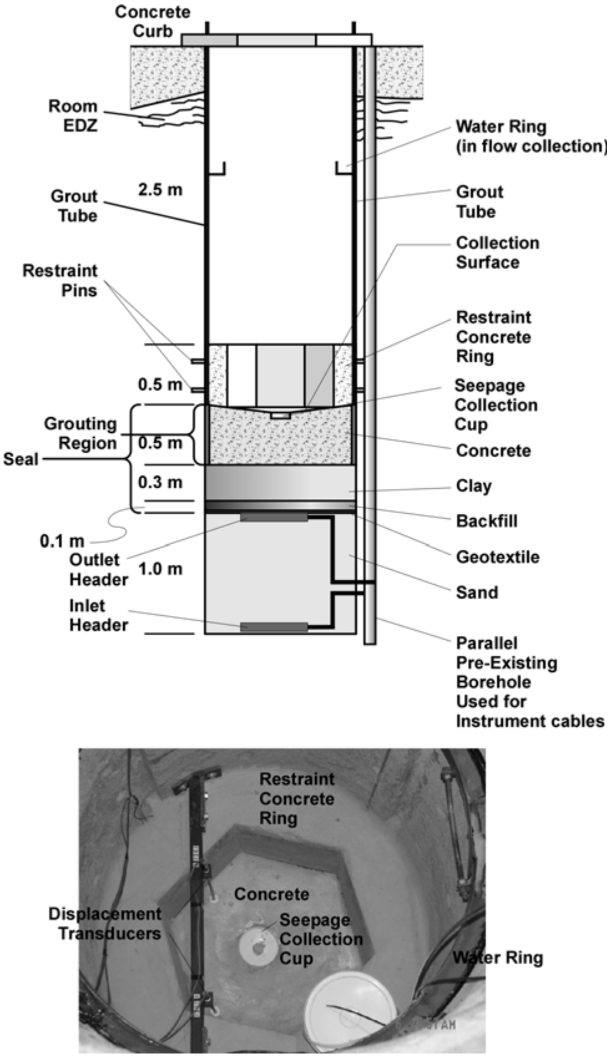

Figure 2: Arrangement of the CSE *(top)* and View of Concrete Layer with Seepage Collection Cup, Concrete Restraint and Displacement Transducers *(bottom)* (Martino et al., 2003).

The composite seal consists of a 0.3-m-thick layer of highly compacted bentonite/sand blocks overlain by a 0.5-m-thick layer of low heat high performance concrete (LHHPC). The composite seal was installed on top of a 1.0-m-thick sand layer placed at the borehole base, which is used as a hydraulic pressurization chamber. A sheet of geotextile and a layer of compacted, lean clay/sand, non-swelling backfill were placed between the sand fill and the bentonite/sand blocks to prevent extrusion of swelling bentonite from the compacted blocks into the sand.

The clay block layer comprises three individual layers of blocks, oriented with a 60° offset to each other to minimize the possibility of a vertical joint remaining open between the blocks. The blocks, nominally 0.1 m x 0.36 m x 0.20 m in size, are composed of 70% Kunigel V1 bentonite clay and 30% graded silica sand and are the same as the blocks used to construct the TSX clay bulkhead. Kunigel VI has a montmorillonite content of 48%. The blocks were fabricated in a modified Adobe block compactor. The average dry density of the blocks was 1.9 Mg/m^3 (effective montmorillonite dry density (EMDD) of 1.2 Mg/m^3). At this density and permeated with potable water, the swelling pressure is about 1 MPa, and the hydraulic conductivity is about 10^{-12} m/s (Chandler et al. 2002a). The clay and sand components were blended in 2 Mg batches and moisture conditioned to a gravimetric moisture content of 14.5%. Gaps between the blocks and between the blocks and the borehole wall were filled with crushed block particles.

The 0.5-m-thick concrete plug is composed of LHHPC, developed by AECL (Gray and Shenton 1998). The LHHPC is produced through substantial replacement of Portland cement by pozzolanic silica fume and non-pozzolanic silica flour. This lower cement content reduces the heat of hydration, which is beneficial for the construction of large volume structures like a seal. Moreover, with the low cement content, LHHPC has a pH of less than 10, while the pH of conventional concrete is 12.4 or higher. LHHPC has little or no free lime (calcium hydroxide) and hence, will not have adverse chemical reactions with bentonite clays. The workability of the product is provided by the addition of a naphthalene-based superplasticizer. Coarse and fine aggregates can be the same as those used in conventional concretes. The LHHPC has a 28-day strength in excess of 70 MPa. The hydraulic conductivity of the concrete was measured to be less than 10^{-13} m/s (Chandler et al. 2002a). The high strength, low hydraulic conductivity, low heat of hydration, and low pH, make the LHHPC a recommended material for use in a repository, particularly when the concrete is to be used in close proximity to swelling clays. However, as with all concretes, proper mix design and curing conditions are necessary for successful installation.

A cup was cast into the top of the concrete layer (see Figure 2) to allow collection and measurement of seepage vertically upwards past the composite seal. In addition, grout tubes were installed to allow grouting of the concrete plug/rock interface. Restraint to confine the swelling clay/concrete composite seal, if the bond and shear resistance of the concrete plug/borehole wall are exceeded, is provided by a separately poured concrete restraint ring. This upper concrete ring is keyed to the borehole wall with steel restraint pins.

An array of 45 instruments measures hydraulic pressure in the sand zone below the composite seal, total suction and total stress in the clay layer, strain and displacement of the concrete plug and temperature. Instrument leads were passed through a parallel cable borehole that was also used for the hydraulic pressurization lines (see Figure 2). Hydraulic pressure is applied to the sand chamber using a static water head system.

Installation of the experiment commenced in 2001 April and was completed by 2002 February. The sand chamber was filled with potable water and saturated in 2002 April.

3 CSE OPERATION AND MONITORING

3.1 Operation

Hydraulic pressurization of the sand chamber commenced on 2002 May 1. The pressure in the chamber was raised by approximately 100 kPa/week. The maximum (and current) hydraulic pressure of 2.35 MPa (240 m of hydraulic head) was achieved at the end of October 2002. The gradual increase in hydraulic pressure was to allow the bentonite/sand blocks time to swell and self seal, avoiding the type of piping and leakage that occurred through the clay bulkhead in the early stages of the TSX (Chandler et al. 2002a).

The applied hydraulic pressure was held constant at ~2.35 MPa from the end of 2002 October until 2003 June 18. On 2003 June 18, the sand chamber was depressurized and the concrete plug/rock interface was grouted with ultra-fine cement-based grout. This grouting was carried out primarily to assess the reduction in seepage flow rate that could be achieved. In addition, this grouting activity, being carried out in a well-controlled, well-characterized in situ environment, would add to the knowledge base for the application of high performance, cement-based grouts for repository sealing. After allowing several days for the grout to set up and cure, the sand chamber was repressurized to 2.35 MPa in three pressure increments from 2003 June 23 to June 25.

From 2003 November 6 to November 7, the experiment was once again depressurized and a tracer solution of sodium iodide and fluorescein was injected into the sand chamber. The chamber was repressurized to 2.35 MPa on 2003 November 7 once the tracer injection was complete. The purpose of the tracer test was to determine seepage velocities and solute transport properties of the seal during the test and to observe flowpaths through the composite seal system when the experiment was decommissioned and disassembled.

3.2 Monitoring Results

The primary measure of the composite seal performance is the rate of water seepage past the seal. Seepage was not observed until the applied hydraulic pressure exceeded 1640 kPa and was not measurable until the pressure reached 1840 kPa (Figure 3). As Figure 3 indicates, the seepage rate gradually decreased from ~0.04 mL/min to ~0.025 mL/min over the period 2002 October to 2003 June. This decrease in flow rate is likely associated with hydration and swelling of the clay. The concrete plug/rock interface grouting in 2003 June had a negligible impact on the seepage, with the flow rate remaining at ~0.025 mL/min. No measurable seepage has been collected after the tracer was injected in 2003 November.

Responses of the psychrometers are shown in Figure 4. As described in Fredlund and Rahardjo (1993), psychrometers are used to measure total suction of an unsaturated soil by measuring the relative humidity of the gas phase in the soil pores. The relationship between relative humidity and total suction is then used to estimate the degree of saturation within the clay. As indicated in Figure 4, initial suctions ranged from about 3 to 6 MPa. The gradual drop in total suction with time indicates that the bentonite/sand blocks are taking up water. A sharp drop to zero suction, as shown, for example, by psychrometer PS01 in 2002 June, likely indicates that the wetting front has moved past the psychrometer location. The psychrometer responses indicate that the wetting front penetrated most rapidly

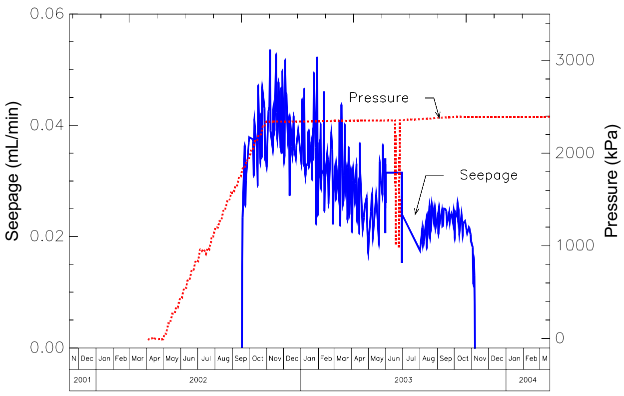

Figure 3: Seepage Rate and Hydraulic Pressure

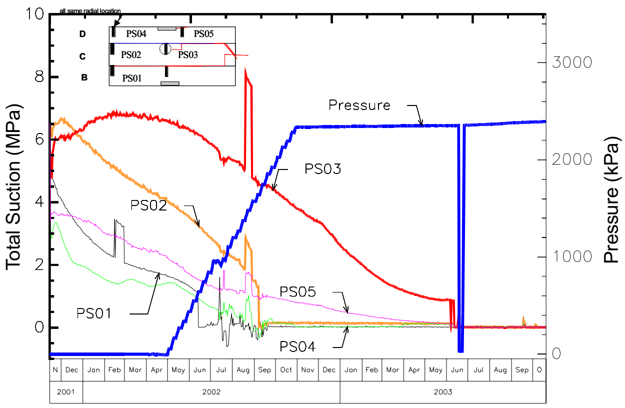

Figure 4: Total Suction Measurements from Psychrometers and Hydraulic Pressure. (Inset Figure Shows Locations of Psychrometers Within the Clay Block Layers B, C and D.)

along the outside perimeter of the clay layer (i.e. rapid decrease in suction in PS01, PS02 and PS04) with the core showing a more gradual saturation rate (i.e. slow decrease in suction of PS03 in the centre of the clay layer). This is a similar pattern to that observed for the TSX clay bulkhead, where the interface provided the preferred flow path for seepage (Martino et al. 2003). By early 2003, the clay layer appeared to be largely saturated, except for the core. The sharp drop of the psychrometer PS03 reading to zero suction in 2003 June indicates that the wetting front had reached the central core of the clay layer and that the clay layer was likely completely saturated at this point in the test.

Responses of the earth pressure cells TPC1 and TPC2, measuring vertical total stresses, are shown in Figure 5 while responses of the earth pressure cells SPC1 and SPC2, measuring horizontal total stresses, are shown in Figure 6. TPC1 is located at the base of the clay layer while TCP2 is located at the top of the clay layer. SPC1 and SPC2 are located within the middle clay block layer, near the borehole wall. TPC2 has likely malfunctioned and is thus not providing reliable data.

Figures 5 and 6 indicate that the total stresses responded to the changes in the applied hydraulic pressure and the development of swelling pressure with water uptake. TPC1 at the base of the clay layer virtually tracked the increase in hydraulic pressure, while SPC1 and SPC2 showed an initial lag of responding to the hydraulic pressure response of about 2 months. The response to changes in hydraulic pressure is particularly evident when the sand chamber was depressurised in 2003 June for the grouting and 2003 November for the tracer injection. As indicated in Figures 5 and 6, the total stress changes virtually tracked the changes in applied hydraulic pressure.

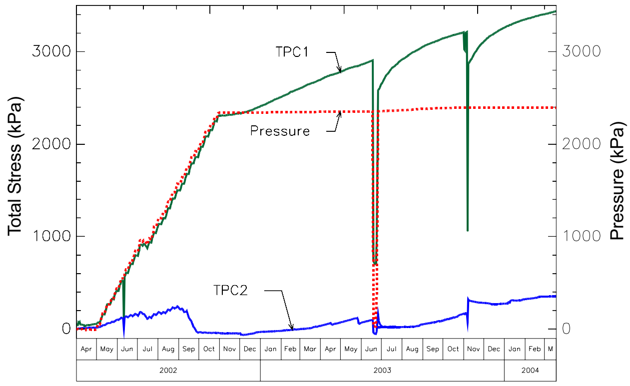

Figure 5: Vertical Total Stresses at the Base (TPC1) and Top (TPC2) of the Clay Layer and Hydraulic Pressure.

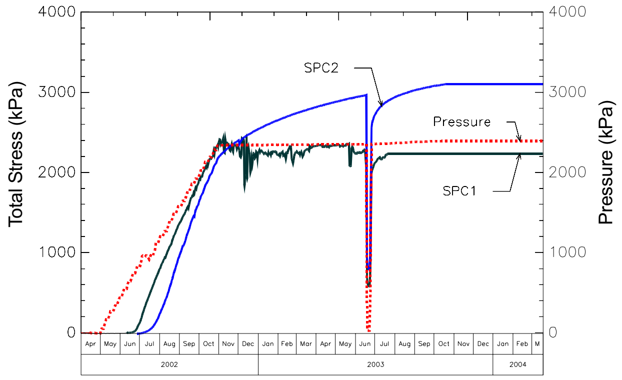

Figure 6: Horizontal Total Stresses and Hydraulic Pressure.

The swelling pressure is equal to the measured total stress minus pore pressure (i.e. an effective stress). If it is assumed that the pore pressure is equal to the applied hydraulic pressure at the earth pressure cell locations, TPC1 and SPC2 are showing swelling pressures of about 1000 and 700 kPa, respectively. These swelling pressures closely correspond to the expected value of 1.0 MPa, as noted in section 2. SPC1 has showed no pressure development in excess of the applied hydraulic pressure and was quite erratic in late 2002 and the first half of 2003. This cell may be malfunctioning.

Figure 7 shows the responses of vibrating wire strain meters embedded within the concrete plug. The concrete plug was poured on 2001 November 15. Most of the strain, which is compressive, has occurred immediately after pouring of the concrete and is associated with shrinkage during curing. Longer-term strain, including that associated with application of the hydraulic pressure, is minimal. The similar strain responses of VSM1 and VSM2 show that strains are quite uniform within the concrete plug.

As shown in Figure 2, two displacement transducers (LVDT1 and LVDT2) are used to monitor displacement of the top of the concrete plug. The responses are shown in Figure 8. Displacement of the concrete plug is upward, as expected. The displacement of the top of the concrete plug is uniform, with only about a 100 micro-metre (µm) difference between the LVDT1 and LVDT2 responses. The displacements responded to the changes in the applied hydraulic pressure. The LVDT responses during the hydraulic unload-reload cycles in 2003 June (for grouting) and in 2003 November (for tracer injection) indicate that the displacements, while relatively small (300 to 400 µm or 0.3 to 0.4 mm), were largely plastic, with little of the displacement being recovered on hydraulic unloading. With total displacements of 0.3 to 0.4 mm, it is likely that not much of the shear resistance of the concrete/rock interface has been mobilized and that the interface has remained bonded.

4 DISCUSSION

As noted previously, the primary measure of performance of a seal is seepage past the seal. Following Chandler et al. (2002b), hydraulic performance of a seal may be assessed by calculating the effective hydraulic conductivity; i.e. dividing seepage rate by the hydraulic gradient and the cross sectional area of the sealed opening. For the composite seal, assuming a seal thickness of 0.8 m (the combined thickness of the concrete plug and clay layer) and a total hydraulic head loss of 240 m (i.e. 2.35 MPa applied hydraulic pressure), the hydraulic gradient across the seal is 300 m/m. Using a seepage rate of 0.025 mL/min (4.2×10^{-10} m^3/s), borehole cross sectional area of 1.21 m^2 and hydraulic gradient of 300 m/m gives an effective hydraulic conductivity of 1.2×10^{-12} m/s.

For the TSX, at ambient temperature and a hydraulic pressure of 4 MPa, the seepage past the concrete and clay bulkheads was 10 and 1 mL/min, respectively, after

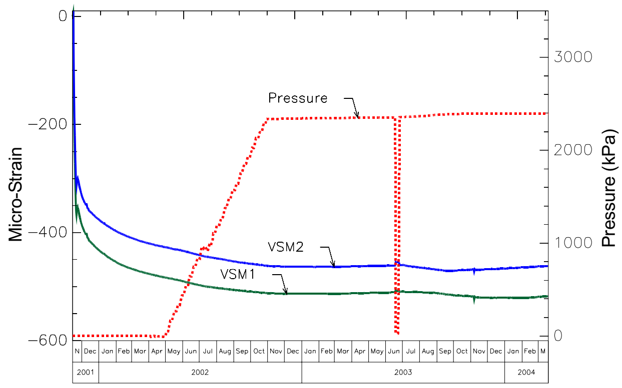

Figure 7: Strains Within the Concrete Plug and Hydraulic Pressure. Decreasing Micro-Strain is Compression.

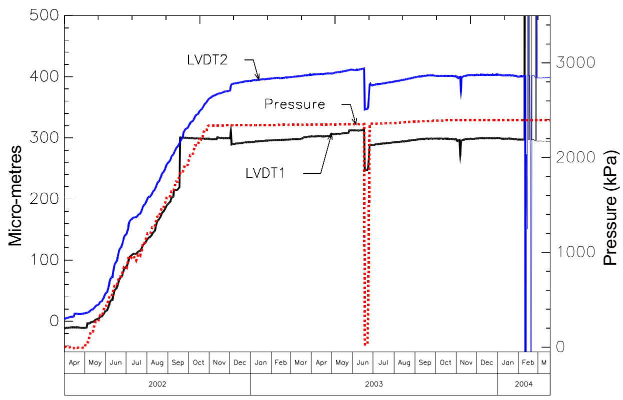

Figure 8: Vertical Displacement of the Concrete Plug and Hydraulic Pressure. Increasing Micro-Strain is Upward Displacement.

approximately 1400 days of operation. These seepage rates give effective hydraulic conductivity values for the clay and concrete tunnel bulkheads of 8.6×10^{-12} m/s and 1×10^{-10} m/s, respectively (Martino et al. 2003). The effective hydraulic conductivity of the composite seal, therefore, is almost an order of magnitude lower than the TSX clay bulkhead and two orders of magnitude lower than the TSX concrete bulkhead.

For the TSX, seepage is believed to have primarily occurred along the concrete/rock interface for the concrete bulkhead and through the lower density shot-clay between the bentonite/sand blocks and the rock for the clay bulkhead (Martino et al. 2003). The concrete bulkhead/rock interface was successfully grouted early in the TSX hydraulic testing phase with the same ultra-fine cement-based grout that was subsequently used in the CSE grouting. Chandler et al. (2002b) note that "It was concluded that the grout was successful in penetrating and sealing the entire concrete-rock interface…" and "…concrete-rock interface grouting was effective in reducing the rate of flow past the concrete bulkhead by three orders of magnitude". Thus, it is unlikely that the hydraulic performance of a concrete bulkhead in a repository would be significantly superior to the observed performance of the TSX concrete bulkhead. In sealing a vertical opening, such as the CSE, the concrete is forced by gravity radially against the opening walls. In the TSX, a gap would tend to form on the upper surfaces of the seal.

Grouting the TSX concrete bulkhead reduced the seepage flow rate and the effective hydraulic conductivity by three orders of magnitude, yet grouting the concrete plug/rock interface of the CSE with the same ultra-fine cement-based grout had minimal effect on the flow rate (see Figure 3) and effective hydraulic conductivity. The reason may lie in the width of the interface aperture.

Following Chandler et al. (2002b), flow through the interface may be simulated as a fracture with finite aperture using a parallel plate model (i.e. the cubic law) as follows:

$$Q = l\frac{b^3 \gamma g}{12\mu} i \qquad [1]$$

where Q = flow rate, l = length of interface (i.e. circumference of the opening being sealed), b = aperture of the interface, μ = dynamic viscosity of water, γ = density of water, g = gravitational acceleration and i = hydraulic gradient. With flow rate in mL/min and b and l in metres, equation [1] reduces to:

$$Q = 3.27 \times 10^{13} \cdot b^3 \cdot l \cdot i \qquad [2]$$

Before grouting of the TSX concrete bulkhead, the measured seepage rate was 1500 mL/min under a chamber hydraulic pressure of 300 kPa (i = 5) (Chandler et al. 2002b). The TSX tunnel circumference (l) is equal to 12.4 m. Using equation [2] with these values gives an aperture of 90 μm. After grouting, the seepage flow rate was reduced to 1.8 mL/min under a chamber hydraulic pressure of 800 kPa (i = 13). These values give a hydraulic aperture of 7 μm. For the ultra-fine cement-based grout used to grout the interface, 90% of the particles were <10 μm in size and the average particle size was 4 μm (Kjartanson and Thompson, 2003). These sizes of grout particles were able to effectively penetrate and seal the 90 μm wide, pre-grouted interface.

For the CSE, the seepage flow rate and applied hydraulic gradient immediately following the establishment of measurable seepage in 2002 September (see Figure 3) are used to calculate the hydraulic aperture. At this time, both the vertical and horizontal total stresses (Figures 5 and 6, respectively) were very nearly equal to the applied hydraulic pressure, indicating that significant swelling pressure had not developed. The impact of the clay layer in reducing measurable seepage through the seal system and through the concrete plug/rock interface would also be at a minimum. Therefore, using equation [2] with Q = 0.04 mL/min, a seal thickness of 0.8 m, i = 235 (using an applied hydraulic pressure of 1840 kPa equal to 188 m hydraulic head), and l = 3.9 m, gives an interface aperture b = 1 μm. If it is postulated that the concrete plug has this order of aperture width, this could account for the relative ineffectiveness of grouting the concrete plug/rock interface of the CSE. Even using the ultra-fine grout with average particle sizes of 4 μm, the grout particles would have been too large to effectively penetrate and seal the 1 μm wide aperture. This narrow aperture width also may be the reason why measurable flow past the seal ceased after the injection of tracer. The fluorescein dye may have increased the viscosity of the tracer solution enough to prevent entry of the tracer into the narrow aperture interface, thus effectively shutting down the flow.

It is also conceivable that seepage past the seal is confined to a very small, localized pathway along the seal/rock interface that the grout didn't penetrate and seal, and not through a narrow, uniform aperture as assumed with the parallel plate model. The only sure means to address the questions of why the grouting was relatively ineffective and why seepage ceased after injection of the tracer solution is through a careful post-test disassembly of the experiment, as described below.

When compared with the concrete bulkhead, the TSX clay bulkhead provided superior hydraulic performance in the longer term, but was susceptible to large scale leakage in the short term before hydration, swelling and self-sealing of the shotclay-compacted clay block system. Several large-scale leaks (up to 20,000 L) were experienced past the clay bulkhead in the early stages of the hydraulic testing (Chandler et al. 2002a). In addition, a bulkhead composed of compacted clay blocks requires rigid structural restraint, such as that provided by the steel support in the TSX or concrete in the CSE. This restraint minimizes volume expansion that would otherwise result in loss of hydraulic effectiveness of the seal, resists potential deformations and, if it is massive, resists erosion associated with seepage forces.

A composite concrete/clay seal would provide optimal performance when employed as a repository bulkhead seal or plug. The concrete plug portion provides effective structural restraint for the clay seal and reduces the potential for high-flow leaks past the clay seal, particularly in the early stages before the clay seal has hydrated and self sealed. This is particularly important for seals that isolate permeable fracture zones, such as seal “C” shown in Figure 1. In the longer term, the hydrated clay seal would provide effective long-term hydraulic performance, superior to that provided by a concrete plug on its own. Moreover, the swelling pressure of the hydrated clay seal lowers interface flow and transport, closes any circumferential fractures in the excavation disturbed zone surrounding the sealed opening and tends to reduce the thickness of the concrete plug/rock interface through the Poisson effect.

An important issue with respect to clay seals is their manner of construction. Two methods are available: use of compacted blocks and in situ compaction. Use of compacted blocks to form the clay seal offers the advantages of excellent quality control on mix and compacted density specifications, independent of the underground conditions, and achievement of high EMDD values (Kjartanson et al. 2003). Disadvantages of the use of compacted blocks are that they require a level working surface for placement, interfaces and gaps between the blocks and between the blocks and the excavation wall need to be filled, and their placement is more labour intensive than in situ compaction. Gap fill materials cannot be placed to as high an EMDD as the compacted blocks. As demonstrated by both the TSX and CSE, the filled gap between the excavation and the clay blocks can result in relatively rapid, three dimensional water uptake by the clay seal and can also offer preferential flow and transport pathways before full hydration of the clay seal. While in situ compaction would not require the placement of lower EMDD gap fill material, particularly at the interface with the rock, the achievable EMDD of the placed clay seal material would not be as high as could be achieved with compacted blocks. Moreover, headroom limitations in the crown region of a tunnel seal would require an alternate placement approach, such as the use of blocks or a pneumatic placement method.

In any case, optimal performance of a clay seal would be achieved by maximizing the EMDD of the clay seal material. This would require the use of high montmorillonite content bentonite and compacted blocks using 100% bentonite, as opposed to bentonite/sand mixes. The advantages of higher thermal conductivity and improved strength and stress-strain characteristics offered by the sand component for a buffer material are not critical in the clay component of a composite tunnel or shaft seal.

The performance of the CSE composite seal to date indicates that a clay/concrete seal can be used to effectively seal against axial flow along an underground opening. In fact, the composite seal appears to offer superior performance over either a clay seal or a concrete seal alone.

Once the operation of this CSE is terminated, the system should be carefully disassembled, sampled and the samples tested and/or observed to:

- determine the basic physical/mechanical properties of the concrete plug.
- determine the presence or degree of chemical/mineralogical influence of the concrete plug on the clay layer.
- determine the moisture content and dry density distribution within the clay layer.
- determine the condition of the concrete/rock interface, evidence of grout penetration and movement within the interface and fate and transport of the fluorescein and sodium iodide tracers within the system.

In addition, monitoring instruments should be carefully recovered and recalibrated to assess their durability and reliability following extended use in the CSE and the monitoring results and results of the decommissioning sampling, testing and observations should be used in a history matching modelling exercise. This would facilitate further development of modelling tool capabilities to assist with the design and assessment of seals in a deep geologic repository.

While this CSE has been most informative regarding the large-scale, in situ performance of a composite seal, it is recommended that further testing be carried out to examine the effects of different seal geometries, including the use of a keyed seal, underground opening wall damage, permeation by high salinity groundwater and elevated system temperatures.

5 SUMMARY

The CSE is examining the in situ performance of a composite seal consisting of a 0.3-m-thick layer of highly compacted bentonite/sand blocks overlain by a 0.5-m-thick plug of LHHPC. The composite seal was installed in a 1.24-m-diameter, 5-m-long vertical borehole on top of a 1.0-m-thick sand layer placed at the borehole base. The sand chamber was saturated with potable water and gradually pressurized to 2.35 MPa over a period of about 6 months.

At an applied pressure of 2.35 MPa, giving a hydraulic gradient of 300 m/m, the flow rate past the seal is low, giving an effective hydraulic conductivity of 1.2×10^{-12} m/s. This effective hydraulic conductivity is almost an order of magnitude lower than the TSX clay bulkhead and two orders of magnitude lower than the TSX concrete bulkhead and is about the same as the laboratory-determined value for the clay block material. This improved hydraulic performance is in part likely due to the relative ease of installing a seal in a vertical opening (e.g. like the CSE) as opposed to a horizontal opening (e.g. like the TSX).

Psychrometers installed in the CSE clay layer indicate that it took over one year for the clay layer to saturate. The psychrometer readings also indicate that water has preferentially migrated along the clay block/rock interface and through the interfaces between clay blocks, giving three dimensional water uptake. This is similar to the water uptake and distribution patterns observed in the TSX. The results of both the CSE and the TSX indicate that careful attention must be paid to sealing of the interface between the clay seal and the excavation wall. This interface could potentially form a preferential pathway for contaminant transport. To mitigate this, the thickness of gap-fill-type materials to seal interfaces should be minimized and when applied, these materials should be placed to as high an EMDD as possible. Furthermore, optimal performance of a clay seal would be achieved by maximizing the EMDD of the clay seal material through the use of high montmorillonite content bentonite and compacted blocks using 100% bentonite, as opposed to bentonite/sand mixes.

The CSE earth pressure cells indicate that vertical total stresses are similar in magnitude to horizontal total stresses and that swelling pressures up to ~1000 kPa have developed within the clay layer. These swelling pressures agree closely with the laboratory-determined value for the bentonite/sand block material.

Approximately 0.3 to 0.4 mm of vertical upward displacement of the CSE concrete plug has occurred. The displacements corresponded directly to changes in the applied hydraulic pressure. It is likely that not much of the shear resistance of the concrete/rock interface has been mobilized and that the interface has remained bonded. In addition, strains within the concrete plug after the curing period have been minimal. Grouting of the concrete plug with ultra-fine cement based grout did not significantly reduce the seepage flow rate. Analysis using parallel plate flow theory indicates that the interface aperture may be too narrow to allow penetration of the grout, but alternatively, the seepage may be confined to a small, localized pathway along the seal/rock interface that the grout didn't penetrate and seal. This issue needs to be further investigated during the CSE decommissioning.

The CSE has demonstrated that a concrete/clay composite seal would be an effective means to seal an emplacement room in a repository and to isolate regions of high groundwater flow from the rest of the repository. Further testing to examine the effects of the use of a keyed seal, excavation wall damage, permeation by high salinity groundwater and elevated system temperatures would provide valuable performance information and should be carried out.

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