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Abstract

A series of 27 large-scale tests have been completed at the 420 level of SKB's Äspö Hard Rock Laboratory. These tests have examined the influence of natural Äspö fracture zone water on the movement of water into and through assemblies of Friedland clay blocks and bentonite pellets/granules. These tests have established the manner in which groundwater may influence backfill and backfilling operations at the repository-scale.

Tests have established that it is critical to provide a clay block backfilling system with lateral support and confinement as quickly as possible following block installation. Exposure of the blocks to even low rates of water ingress can result in rapid loss of block cohesion and subsequent slumping of the block materials into the spaces between the blocks and the tunnel walls. Installation of granular or pelletized bentonite clay between the blocks and the walls resulted in a system that was generally stable and not prone to unacceptable short-term strains as water entered.

Inflow of water into a backfilled volume does not result in uniform wetting of the pellet/granule – filled volume and as a result there is the potential for rapid movement of water from the point(s) of ingress to the downstream face of the backfill. Depending on the inflow rate and flow path(s) developed this flow can be via discrete flow channels that are essentially non-erosive or else they can develop highly erosive flow paths through the clay block materials. Erosion generally tends to be highest in the period immediately following first water exit from the backfill and then decreases as preferential flow paths develop to channel the water directly through the backfill, bypassing large volumes of unsaturated backfill.

At the scale examined in this study inflow rates of 0.1 l/min or less do not tend to be immediately problematic when the source is 0.6 m distant from the downstream face of the backfill. At larger scales or longer distances from the working face, it is likely that the backfill can handle somewhat higher inflow rates and provide a longer time period before exiting the backfill. This would provide more capacity to handle interruptions in backfilling operations before remedial actions will be necessary to ensure backfill competence. Based on preliminary data the quantity of material removed by water flowing into and past the backfill in the first 48 hours after inflow begins will range from 0 to 35 g/l. Beyond 48 hours the erosion rate drops to 5 to 15 g per litre of water through-flow. It is flow amount rather than rate that will etermine the amount of material removed by water movement along the rock-pellet interfaces. These data provide guidance to the planning andconduct of larger (1/2 scale) tests that will quantify the effects ofscale, time, flowpath length and iflow rate on backill perfrmac

Sammanfattning

En serie på 27 storskaliga tester på 420 m djup har gjorts på Äspölaboratoriet. Vid dessa tester har man undersökt vilken påverkan vatten från Äspös naturliga sprickzoner har på vattenrörelser in och genom staplar av friedland block och bentonit pelletar/granulat. Dessa tester har påvisat hur grundvatten kan påverka återfyllningen och återfyllningsprocessen i vid slutförvarsdjup.

Testerna har visat att det är kritiskt för återfyllningen att man förser staplarna av återfyllningsblock med lateralt stöd så snart som möjligt efter blockinstallationen. Även om blocken utsätts för lågt vatteninflöde kan det resultera i att blocken snabbt faller isär med efterföljande ras av blockmaterial i utrymmet mellan block och tunnelväggar. Installation av granulat eller pelletiserad bentonitlera mellan block och vägg resulterade generellt i ett stabilt system.

Vatteninflöde till en återfyllningsvolym resulterar inte i en homogen bevätning av den fyllda volymen pelletar/granulat, som ett resultat av detta finns möjlighet för snabb vattenrörelse från punkten för inflöde till fronten på återfyllningen. Beroende på inflödeshastighet och hur flödesvägarna breder ut sig kan detta flöde utvecklas till distinkta kanaler som i huvudsak är icke-erosiva eller så kan de utvecklas till högerosiva flödesvägar genom lerblockmaterialet. Generellt tenderar erosion till att vara högst i perioden direkt efter att första vettengenombrytningen från återfyllnignen sker och minskar sedan när flödesvägar utvecklas för att kanalisera vattnet direkt genom återfyllningen och leds då förbi stora volymer av omättad återfyllning.

I den skala som undersöktes i denna studie är inte inflödeshastigheter på 0,1 l/min eller lägre uppenbart problematiska när källan är 0,6 m från återfyllningsfronten. I större skala eller på längre avstånd från fronten är det troligt att återfyllningen kan hantera något högre flöden och det tar längre tid för vattnet att bryta genom återfyllningen. Detta ger bättre kapacitet att hantera avbrott i återfyllningsprocessen innan avhjälpande åtgärder behövs för att säkerställa återfyllningens kvalitet. Baserat på preliminära data varierar kvantiteten på bortfört material med vattnet som flödar in och förbi återfyllningen under de första 48 timmarna mellan 0 till 35 g/l. Efter 48 timmar minskar erosionen till 5–15 g/l. Det är snarare storleken på flödet än hastigheten som bestämmer mängden material som bortförs av vattenrörelser längs berg-pellets kontaktytan. Dessa data ger riktlinjer för planering och utförande av större (1/2-skala) tester som kommer att kvantifiera effekterna av skala, tid, flödesvägens längd och inflödeshastighetens påverkan på återfyllningens funktion.

Acknowledgements

This work was supported by SKB and Posiva as part of the BACLO project. The assistance of the SKB staff in conduct of water content analyses and other contractors to SKB (in particular M. Hedin and E. Örtendahl) in the construction, dismantling and operation of the field tests and monitoring system are gratefully acknowledged. Professor R. Pusch provided valuable review comments on this document and his assistance is gratefully acknowledged.

Contents

1 Background

The sealing of a repository for used nuclear fuel requires the installation of backfilling materials within the rooms, tunnels and other openings. This material has a number of functional requirements including the ability to take on water from the surrounding rock and swell to produce a material that is of adequately low permeability as well a ensuring that there are no persistently open pathways for water flow. The backfilling option being considered by SKB and POSIVA is the installation of precompacted blocks of limited swelling capacity and pellets of clay having a high swelling capacity. The blocks would occupy the majority of the tunnel volume while the pellet materials would be used to fill the spaces where block placement is not possible (spaces adjacent to tunnel walls, roof and tunnel floor).

The installation of a backfilling system composed of blocks and pellets has a number of potential challenges, particularly with regards to initial system stability under conditions of localized water influx. The presence of substantial water influx, especially when localized makes placement of the backfilling materials difficult and in extreme cases such influx may cause localized erosion of the backfill and loss of mechanical stability prior to the completion of local backfilling operations.

This study examines the manner in which water enters into and is distributed within a volume of backfill installed in a geometry similar to that proposed for tunnels and rooms. Of particular concern are situations where backfilling operations were interrupted for some length of time, without installation of a temporary or permanent plug. It is intended that studies such as the one described in this report will lead to identification of some limiting criteria for water influx rate, above which some remediation of the surrounding rock would be necessary. This threshold determination will provide guidance to planning of repository backfill operations. This will also help to identify conditions where special water control will be necessary (e.g. drainage, grouting or alternative backfilling approach) in order to achieve effective backfill placement.

2 Objectives and outline of testing program

This study is intended to examine the basic properties of a simulated tunnel that has been backfilled using precompacted backfill blocks and bentonite pellets. In the tests done as part of this study the effect of varying water influx rate from a point source on the backfilled tunnel section have been examined. Of particular interest is the manner in which water is taken into the pellet-filled volume and the time that passes between start of water influx and its appearance as outflow at the downstream end of the backfilled volume. From the information collected in this study it is intended that an approximate limit for allowable water inflow into a tunnel section be identified and also a timescale for such breakthrough to occur. From this information it is possible to estimate both the hydraulic inflow limits for the tunnel section as well as helping to determine the rate of backfill placement that is necessary to avoid possible erosive activity caused by such a point source of water.

It should be noted that these tests are not actual field-scale tests done in a natural rock environment so the results are indicative only, providing guidance for the preliminary planning of backfilling operations. In a repository environment additional factors such as multiple or non-point sources of water supply, the presence of excavation damage in the surrounding rock and a larger scale of both blocks and pellets will exist. From the tests described in this report it is intended that larger, field-scale tests be planned and carried out to extend the knowledge base further towards repository-scale application.

The tests described below also include evaluation of the effects of leaving clay block assemblies in a dry tunnel section where no water influx occurs and no pellet fill has been installed; the effect of gaps between clay blocks; and of water dripping directly onto clay block assemblies prior to pellet placement.

3 Test setup, description and materials used

3.1 General description of test setup

In the course of this testing program a total of 27 tests were done. Conditions applied to the clay block and block-pellet assemblies were varied to evaluate system evolution under differing environmental conditions. As this testing program progressed minor changes in the test geometry were necessary as well as minor modifications to the test set-up equipment in order to improve its operation and improve the quality of the results collected.

This series of experiments were done in SKB's tunnel laboratory in Äspö at the depth of –420 m. In an alcove at this level, 2 concrete chambers, each of two meters diameter by 1.6 m length were installed. The upper half of the concrete chamber was used for testing by divided it from the lower by a stiff plate and then subdividing the upper portion into two parts that are geometrically identical. Tests involving the assembly of a large number of clay blocks (108 to 184 depending on the specific test geometry) in the chamber(s) Figure 3-1 and Figure 3-2 show the layouts of the tests as installed and Figure 3-3 and Figure 3-4 show photos of actual test

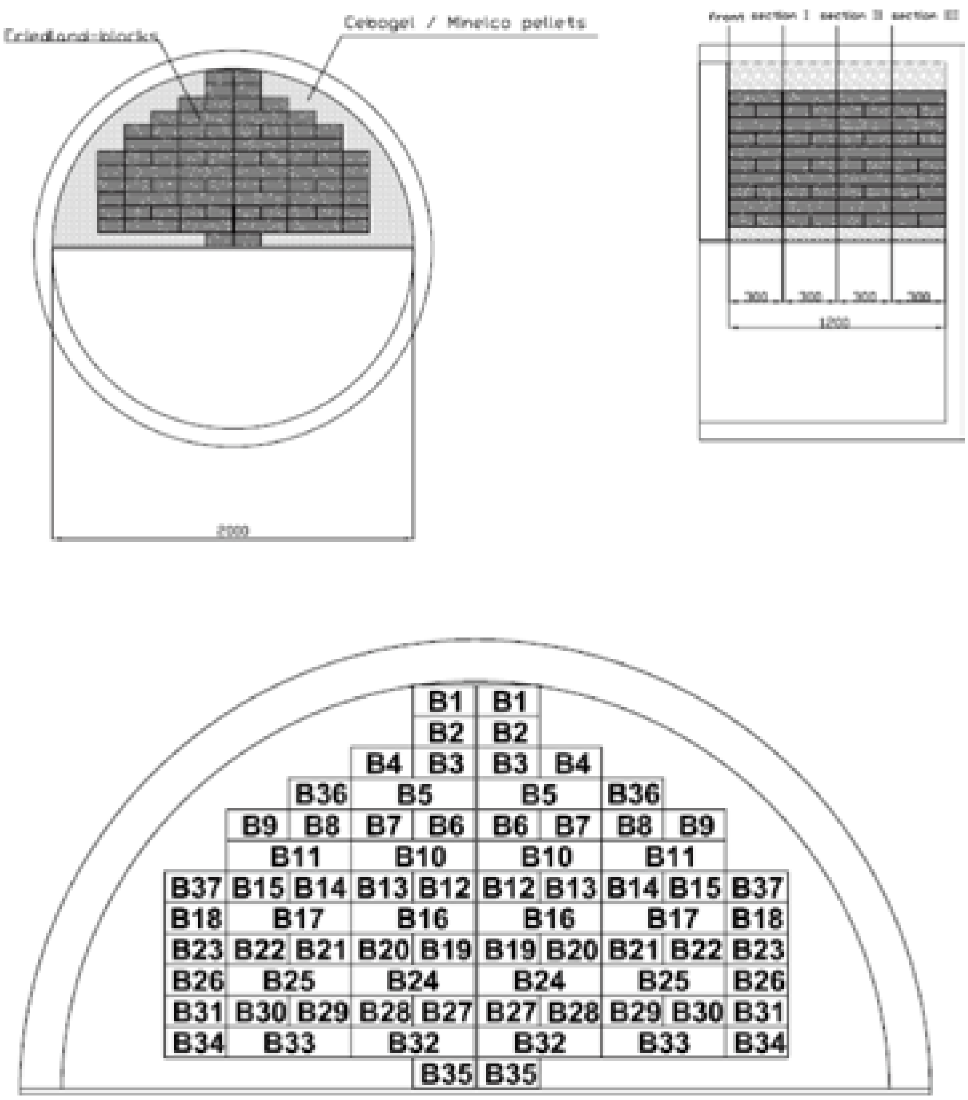


Figure 3-1. General layout of the test chamber and numbering of clay blocks.

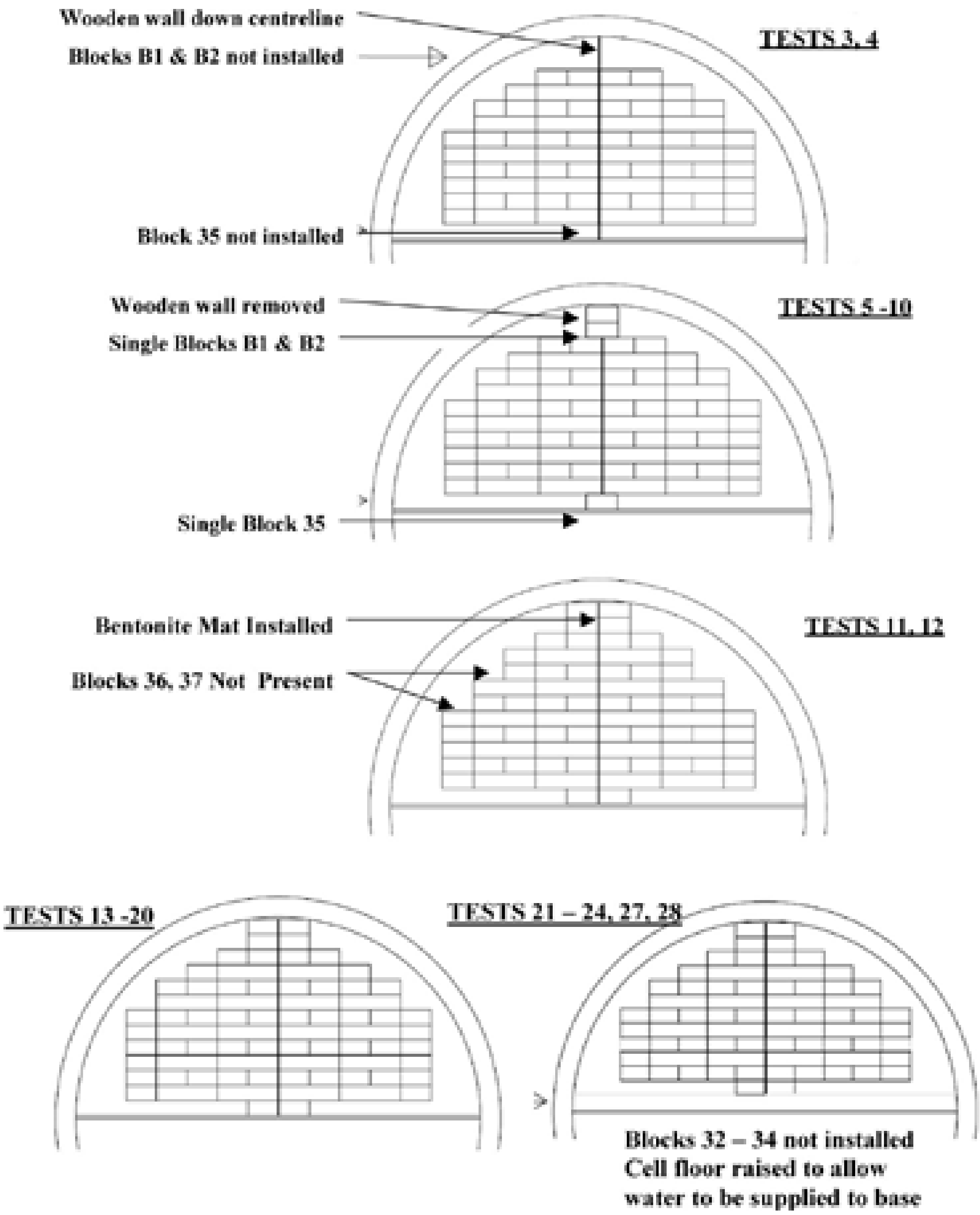
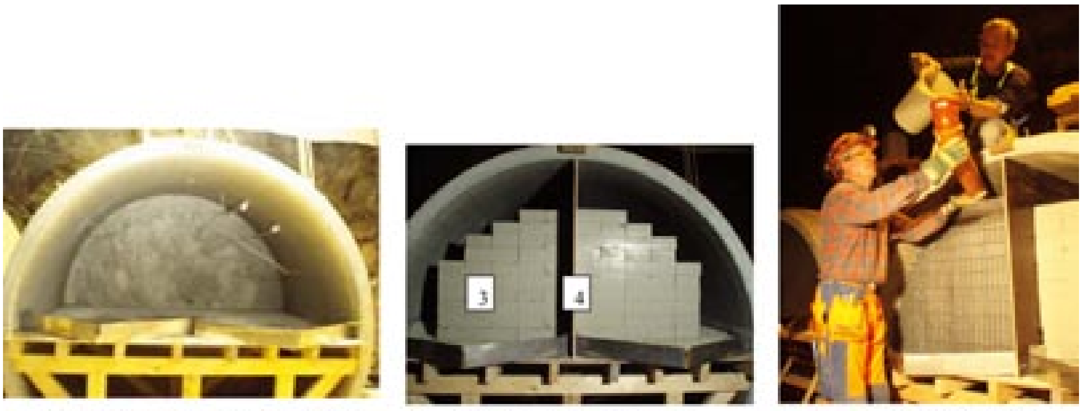


Figure 3-2. *Block assemblies used in BACLO Tests.*

assemblies. The variations in test geometry were in response to a need to improve hydraulic isolation between test sections, to permit water input to base of block assembly and to accommodate changes in the materials used below the blocks (Minelco versus Cebogel). These changes had minor effects on the density of the pellet fill installed but these were included in the analysis of the results. There was no evidence that the minor changes in test set-up had any discernible effect on the results obtained.

The test chamber was divided into two segments in order to facilitate conduct of a larger number of tests. A variety of means were used to differing levels of success in order to hydraulically isolate these two sections. These techniques are discussed later in this test on a test-by-test basis. Where water inflow was part of the test, it was supplied via a line that penetrated the concrete pipe thereby providing a point source for water. The water used to hydrate the tests was natural Äspö water collected from a local fracture. This water was fed into metering pumps that supplied water to the test chambers at preset inflow rates. The resistance to this inflow was monitored and changes in the pressure at the inlet point were interpreted as changes in the physical conditions within the clay- and block-filled volume.



a. Pipe showing water inflow locations

b. Block assemblies on granular base

c. Installing Bentonite Pellets

Figure 3-3. *Test chamber and installation of blocks and pellet materials.*

The swelling of the bentonite pellets as well as the clay blocks as the result of addition of water to the system resulted in the need to provide a substantial degree of restraint at the open face of the test assemblies. Tests 1 and 2 did not have this restraint present due to their unique set-up and purpose (discussed later in this report). The remaining tests required that the assemblies be restrained to some degree to avoid uncontrolled swelling of the system. This restraint system was not however entirely rigid, and underwent a couple of modifications until it was deemed to be functioning as desired (see discussion later in this report). Ultimately it consisted of a mechanically supported fine steel mesh that allowed for unhindered water movement from the assembly as well as for erosion of materials (if occurring). Any exiting water outflow was to be collected in the trays under the block assemblies (Figure 3-4) and then measuring the outflow volumes. Several of the earliest tests encountered difficulties in capturing outflow, resulting in loss of this aspect of the data collection for those tests. In later tests the improved water collection system was also used to estimate the quantity of material eroded from the test set-up during its operation.

The controller for the water supply system is shown in Figure 3-5. Water was supplied at a fixed quantity per minute, simulating seepage provided from a discrete fracture. As resistance to inflow increased, the metering pumps increased the pressure at which they operated in order to continue to supply the same quantity of water per unit time. The maximum pressure measured is interpreted as being equivalent to the swelling pressure generated by the hydrated pellets. This setup is intended to simulate, to some degree, the conditions in an actual tunnel section, increasing resistance to water entry from a fracture is accompanied by a build-up of the hydraulic pressure at the interface between the rock and the backfill until the hydraulic pressure exceeds the ability of the clay to resist it.

Figure 3-4. *Steel mesh restraint and water collection from test chambers.*

Figure 3-5. *Water supply system.*

3.2 General description of tests

A total of 27 tests were done as part of this work. Table 3-1 and Table 3-2 provide brief summaries of these tests and the conditions imposed on them as well as the matrix of testing adopted. The first two tests were substantially different than those done subsequently as they did not include the installation of bentonite pellets in the space between the blocks and the concrete ring. In Test 1 clay blocks were placed in an environment simulating a dry tunnel section prior to pellet placement but where a very humid environment existed. Test 2 examined clay blocks where this same type of backfill block assembly was exposed to a point source of water dripping onto its upper surface. In Test 2 the blocks rested on a base of granular bentonite (Milos/Minelco). The remainder of the tests done in this study used precompacted pellets of bentonite (Cebogel) or granular bentonite (Milos) as base or surrounding material. These tests had water supplied to them via a point source at rates that varied between 0.01 l/min to 1.0 l/min and operated from 5 hours to 5 days before being terminated. This allowed for evaluation of two of the key parameters (inflow rate and time) affecting backfill stability.

At the end of each test, it was dismantled with careful photographic recording of the moisture and physical conditions present at three or more distances from the outer face of the assembly. Samples were also taken from the volume where the pellets were installed in order to evaluate what water distribution has developed as the result of the water influx. Samples of the block materials were also recovered for water content assessment.

Table 3-1. List of tests and conditions imposed.

Test #	Materials Used	Water Inflow Rate (l/min)	Test Duration (hours)	Purpose
1	Clay Blocks	nil	890	Evaluate effects of humidity on blocks
2	Clay Blocks Granular Bentonite	0.1	216	Evaluate effects of inflow dripping directly onto blocks on a granular base
3–8	Clay Blocks Bentonite Pellets	0.01–1.0	5–118	Evaluate water uptake by, transfer through and outflow from a scaled simulation of a backfilled tunnel
9–12	Clay Blocks Bentonite Pellets	0.10; 0.25	5–24	" " also, evaluate effects of gaps between block assemblies.
13–22	Clay Blocks Bentonite Pellets	0.1–0.5	5–100	Evaluate effects of inflow rate and time on water distribution in pellets and blocks
23–24	Clay Blocks Bentonite Pellets	0.10; 0.25	24	Evaluate effect of water inflow from tunnel floor on pellet hydration and water movement
27–29	Clay Blocks Granular Bentonite Bentonite Pellets	0.25	48	Examine effects of water inflow rate on a system built using granular bentonite as a flooring material and pelletized materials as fill for remaining annular space

Table 3-2. Test matrix for water uptake simulations.

	Test Duration (Hours)			
Water Inflow Rate (l/min)	5	24	>48	>100
0,01			7	
0,03			8	
0,1		9, 11, 15	3*, 4**, 17, 21+,	19
0,25	6, 10, 12, 14	16	18, 22+, 28++, 29++	
0,5	13			20
1,0	5			
Floor 0,1		23		
Floor 0.25			27++	
Floor 0,5		24		
Nil				1
0.1 onto blocks				2

Note: Tests 25, 26 planned for but not done, to avoid any uncertainty in records system the numbers were retained.

* Leakage from test chamber occurred so test was repeated (#17). Leakage was also detected in tests 4, 7, 8, 9, (10?).

** Water inflow was via 3 closely spaced points to simulate water influx from a fracture.

+ Minelco crushed bentonite used rather than Cebogel pellets.

++ Minelco on floor and Cebogel surrounding blocks.

4 Materials used

4.1 General description of clay materials

Three clay materials were examined in the course of this study. All of them contain at least some swelling clay mineral content and are considered to be potentially suitable for use in backfilling applications. Two of the high smectite clays used in the study (crushed bentonite and bentonite pellets) are marketed commercially as bentonite (this being the generic commercial name given to high smectite clays formed from volcanic ash originally deposited in the sea or estuarine environments). For ease of reference all three of these materials are distinguished from one another by use of their source or trade names. Details on their mineralogy, chemical characteristics and other key features can be found in Section 4.2.

4.1.1 Friedland clay

Friedland Clay: The raw clay material used to compact these blocks is Friedland clay produced by Friedland Industrial Minerals GmbH in Germany. The blocks shown in Figure 4-1b were manufactured in Sweden by Höganäs Bjuf AB. It is a smectite-rich material that has a limited swelling capacity and is believed to be potentially suitable as a backfilling material in a repository provided it is precompacted to an adequate density. The clay blocks used are produced by the mechanical compaction of a natural clay material with a high content of particles smaller than 2 µm, known commercially as Friedland clay. This clay, used for manufacturing of these blocks has considerably less expandable minerals than clays commonly termed "bentonite". The Friedland material contains approximately 45% expandable minerals versus 80% reported for bentonite) and so is generally referred to as a smectitic clay rather than a smectite clay /Pusch and Yong 2006/.

4.1.2 Minelco and cebogel clay

The crushed bentonite used in this study is known commercially as "Minelco" bentonite and was sourced in Greece. This material was used in Tests 1, 21, 22, 27, 28 and 29 and is shown in its "raw" form in Figure 4-1a. It should be noted that tests 27–29 had Minelco used as flooring and Cebogel was used to fill the remaining unfilled test volume. Information regarding its composition and basic characteristics can be found in Section 4.2.

CEBOGEL QSE pellets are produced as short cylindrical rods by Cebo Holland BV. According to the producer of the pellets, the raw material is activated high-grade Ca-bentonite quarried by Silver & Baryte Mining Company S.A. from Isle of Milos, Greece. This makes the source material for the Cebogel pellets and Minelco granular bentonite the same. Both of these materials are soda ash activated Ca-bentonite. The Cebogel pellets were used in most of the tests done in this study as a floor-levelling material, on which Friedland clay blocks were piled. It was also used to fill the space between the block assembly and concrete walls. Between 735 to 950 kg of pellet materials were used in each pair of tests. The mass varied largely as a function of the specific geometry of the tests (some variations in the number of blocks installed occurred, see Section 3.1) but was measured for each test pair installed. The diameter of each pellet is 6.5 mm and their length is between 5 and 20 mm and can be seen in Figure 4-1c. The producer reports that the bulk density achievable through pouring of pellets is approximately 1,100 kg/m^3 and the density of the individual pellets is 2,100 kg/m^3. The actual dry density of the poured pellet mass was calculated to be between 990 and 1,180 kg/m^3 for the tests done in this study with an average of 1,100 kg/m^3 at the start of testing and the gravimetric water content was measured to average 18.9%. The specifics for each test are presented in Section 6 of this report.

The water used in all of the field tests described in this report was natural formation water taken directly from fracture HD0025A at the Äspö HRL. It has a concentration of dissolved salt (NaCl) of approximately 0.5% (5,000 ppm).

Figure 4-1. *Materials used in testing.*

In Tests 2, 27, 28 and 29 crushed bentonite clay (Milos/Minelco) was used to provide a base for the installation of the backfill block assembly but was not used to fill any other openings in that test. Tests 21 and 22 used Minelco bentonite to fill all the non-block volume. All other tests used the commercially manufactured Cebogel bentonite pellets.

4.2 Mineralogy and chemistry

4.2.1 Friedland clay

Friedland-clay is a smectite-rich clay from northeastern Germany. The deposit is located near the town of Neubrandenburg and the clay has been quarried there for the use of ceramic industry and various civil engineering applications. The clay occurrence is massive and homogeneous with estimated reserve of approximately 100 million tonnes /Karnland et al. 2006/. It is of Tertiary origin and formed by a complex processes including sedimentation, weathering, erosion and hydrothermal alteration /Pusch 2001, Karnland et al. 2006/.

The mineralogy of the material has been studied by several researchers including, /Henning 1971, Pusch 1998, 2001, Carlson 2004 and Karnland et al. 2006/. According to /Henning 1971/ the swelling component of the clay consists of randomly interlayered muscovite/montmorillonite with montmorillonite component dominating. The amount of swelling minerals within the clay has been estimated to be on average 45% /Pusch 1998/. However, also significantly lower values (max 35%) have been reported in /Carlson 2004/ and in /Karnland et al. 2006/ and are also indicated by the results of index tests undertaken by AECL as part of this study (Section 4.3). /Pusch 1998/ reported that other minerals present include quartz (24%), mica (13%), chlorite (11%), feldspar (5%) and carbonate (2%). /Carlson 2004/ describes the mineralogy of the clay as a "mixture of several clay minerals and detrital quartz, feldspars, siderite and small amount of pyrite."

The chemical composition of the Friedland clay determined as oxide percents with XRF is SiO_2 (60%), Al_2O_3 (18%), Fe_2O_3 (7%), MgO (2%), CaO (0.4%), Na_2O (1%), K_2O (3%) and TiO_2 (1%) /Carlson 2004/. /Based on Carlson 2004/, the sulphur and carbon contents are below 1%. The exchangeable cations determined with 0.05 M Cu (II) ethylenediamine at ph 7 within the clay are Na^+ (22.2 $cmol^+$/kg), Ca^{2+} (11.0 $cmol^+$/kg), Mg^{2+} (6.9 $cmol^+$/kg) and K^+ (2.2 $cmol^+$/kg) leading to total cation exchange capacity of 42,3 $cmol^+$/kg /Carlson 2004/.

4.2.2 Minelco and cebogel clay

The Milos clay deposits were formed as a consequence of hydrothermal alteration of volcanic rocks during the Tertiary period /Christidis and Scott 1996/. The clay deposits occur in irregular bodies with thickness of 140 m /Karnland et al. 2006/. The mineralogy and chemistry of Milos bentonites has previously been studied e.g. in /Carlson 2004/ and /Karnland et al. 2006/. The mineralogy and chemistry of Cebogel pellets and Minelco granules were investigated as a part of Posiva's Belake project concerning development of quality control for bentonite clays. The results of the project are reported in /Ahonen et al. 2008/. Table 4-1 shows the estimated mineralogical composition for these materials and compares them to data presented in /Carlson 2004/ and /Karnland et al. 2006/. Based on these analyses the amount of swelling minerals is approximately 80% and the main accessory mineral is calcite (5–15%).

The chemical composition of Cebogel pellets and Minelco pellets determined with XRF /Ahonen et al. 2008/ is presented in Table 4-2. For comparison, the chemical composition of high-grade Milos Ca-bentonite determined by /Carlson 2004/ with XRF and sulphur/carbon analyzer is also presented. The chemical composition of these two materials is very similar, but there are small differences in the amounts of Na_2O and CaO. The observed differences may be due that somewhat higher amount of soda ash (Na_2CO_3) may have been used for activation of Cebogel pellets and the calcite content that is higher in Minelco granules. The chemical composition correlates also fairly well with the high-grade (non-activated) Ca-bentonite from Milos materials reported on by /Carlson 2004/.

Exchangeable cations and cation exchange capacity (CEC) determined by /Ahonen et al. 2008/ for Cebogel pellets and Minelco granules are presented in Table 4-3. For comparison, the data for high-grade non-activated Ca-bentonite (Deponit CA-N (MiR1)) studied by /Carlson 2004/ is also presented. The effects of soda ash activation of Cebogel pellets and Minelco granules can be seen in the results (higher Na^+ and higher CEC compared to non-activated Milos Ca-bentonite). Additionally dissolution of calcite is evident in the NH_4-acetate CEC analyses, especially in case of the Minelco granules and the high-grade Ca-bentonite.

Table 4-1. Mineralogical composition of Cebogel and Minelco materials (results from the Belake project and from /Carlson 2004/ and /Karnland et al. 2006/).

	Cebogel pellets	Minelco granules	Milos high-grade Ca-bentonite /Carlson 2004/	Deponit CA-N (MiR1), non-activated Ca-bentonite from Milos /Karnland et al. 2006/
Montmorillonite	80	80	75–80	81.4
Quartz	<5	<5	<5	0.4
Feldspars	<5	5		0.7
Calcite	<5	10	115	5.5
Dolomite	<5	5		1.3
Illite				4.6
Cristoballite				0.6
Hematite	present			0.2
Goethite				0.4
Muscovite				1.4
Pyrite			<5	1.1
Gypsum				0.4
Lepidocrocite				0.3
Anatase				0.1
Magnetite				0.1
Rutile				0.3
Siderite				0.3
Tridymite				0.4

Table 4-2. Major elements, sulphur and carbon in Cebogel and Minelco (as weight-%).

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	S	C
Cebogel	53.1	16.8	5.2	3.8	5.4	3.5	0.6		0.45	
Minelco	52.0	16.8	5.1	4.0	6.7	2.7	0.8		0.34	
Milos*	48.7	17.3	4.8	3.0	9.3	0.7	0.3	0.8	0.47	0.59

Table 4-3. Exchangeable cations and cation exchange capacity.

		Exchangeable Cations			CEC
	$cmol^+/kg$	$cmol^+/kg$	$cmol^+/kg$	$cmol^+/kg$	$cmol^+/kg$
$BaCl_2$-method	**Ca^{2+}**	**K^+**	**Mg^{2+}**	**Na^+**	
Cebogel	13.3	0.9	7	78.3	99.5
Minelco	10.9	1.0	8.8	62.2	82.9
Milos high-grade Ca-bentonite	32.6	1.7	19.9	21.3	75.47
NH_4-acetate-method	**Ca^{2+}**	**K^+**	**Mg^{2+}**	**Na^+**	
Cebogel	12.2	1.4	8.0	81.3	103,0
Minelco	18.7	1.4	13.2	65.7	99,0
Milos high-grade Ca-bentonite	71.8	1.2	19.9	18.4	111.3
MX-80					109

/Ahonen et al. 2008 and Carlson 2004/.

4.3 Basic geotechnical properties

The original raw material (Friedland clay granular) had granule size between 1 mm and is produced by FIM Friedland Industrial Minerals GmbH in Germany. This material was moisture conditioned and mechanically compacted (via uniaxial compression) to generate bricks. According to preliminary results /Johannesson 2008/ the test blocks produced in Bjuv brick factory in Sweden in July 2006 had water content of 6.3%, bulk density of 1,940 kg/m^3, dry density of 1,820 kg/m^3, degree of saturation of 33% and void ratio (e) of 0.5. The liquid limit of a sample of the Friedland-clay used in these blocks was 112 (%) and the swelling index (ml/2 g) was 4.3%. Based on preliminary results by /Johannesson 2008/, blocks of this density level should yield swelling pressure of approximately 1.5 MPa and have a hydraulic conductivity of $2x1^{12}$ m/s. The compacted Friedland clay blocks used in this test were 300x150x75 mm in dimension, gravimetric water content was approximately 6.3% during the compaction but the dry density is only 1,800 kg/m^3. The estimated pressure used in manufacturing these blocks was only approximately 7 MPa, which was inadequate to achieve the previously specified 2,000 kg/m^3 densities. Clay Technology AB had initially defined the block specifications to be: a water content 8.6% (saturation 62.2%), bulk density 2,200 kg/m^3, dry density 2,000 kg/m^3 and a void ratio of 0.385. On determination of the improper block density a review of the purposes of the tests described in this document and the impact of lower density blocks occurred. It was determined that while these low-density blocks are not of an adequate density for use in an actual repository, for the purposes of these tests where the main focus is on the pellet materials the blocks could be used without compromising the results.

Cebogel QSE is bentonite pressed to cylinder shaped pellets with diameter of 6.5 mm and length of 5-20 mm. According to manufacturers specifications the Cebogel pellets have a dry density of 2,100 kg/m^3 and the bulk density of loosely–poured pellets will be 1,100 kg/m^3.

Minelco material consists of crushed raw bentonite provided as granules with maximum granule size of 10 mm. According to producer of the pellets, Cebo Holland BV, the raw material is activated high-grade Ca-bentonite quarried by Silver & Baryte Mining Company S.A. from Isle of Milos, Greece. According to distributor of the Minelco granules, the origin of this material is same as the Minelco granular bentonite and both are soda-ash activated Ca-bentonite. The granule size distribution of two different batches of Minelco granules obtained approximately 6 years apart is presented in Table 4-4. Based on this the maximum granule size is approximately 10 mm and the fine fraction (<0.063 mm) is 3% but this will vary from batch to batch and as the result of powdering caused by handling of the materials during transportation, storage and placement. If a consistent granularity is needed for this material then considerable quality-control improvement is needed.

The index properties measurements (liquid limit (%) determined with fall-cone test and the swelling index (ml/2g)) determined in Sweden and Finland are presented in Table 4-5 (Clay Technology AB and by /Ahonen et al. 2008/). This information is supplemented by results obtained in Canada that indicate a much lower liquid limit (using Casagrande method) than previously reported for the Friedland clay. The very substantial difference in these measurements cannot be explained by technique or operator and indicate that there is a material consistency issue that will need to be addressed in the future.

For comparison purposes some of the geotechnical properties previously reported for MX-80 bentonite clay are also provided in Table 4-5. These data provide a commonly recognized reference material for bentonite buffer, against which the clay materials being considered as potential components of the backfilling system can be compared, although the requirements are more strict for buffer than for backfill. Tests to determine the swelling pressure for a bulk mass consisting of pellets and granules (without extensive compaction) and assuming no volumetric change in the block materials estimates that the swelling pressure will be approximately 100 kPa.

Table 4-4. Grain-size distribution of Minelco granules.

Grain size (mm)	Minelco 2001 (%)	Minelco 2007 (%)
>4	55	28
>2	34	26
>1	8	22
>0,5	1	11
>0,25	0,5	4
>0,125	0,3	2
>0,063	0,5	4
<0,063	0,4	3
	99,7	**100**

Table 4-5. Liquid limit (%) and swelling index of clay materials used.

	MX-80	Cebogel	Minelco	Friedland
Liquid limit (%)	524^{++}, 518^{+}	576*; 575**	334*; 245**; 316^{+}	57^{+}; 112^{++}
Plasticity Index	483^{+}	>500	280^{+}	34^{+}–89
Swelling index (ml/1g)	20.8^{++}	11.9*	9.7*	4.3^{++}
Swelling index (ml/2g)		28**	30**	

* Unpublished data from Clay Technology AB

** /Ahonen et al. 2008/

$^{+}$ unpublished data from AECL 2007

$^{++}$ /Johannesson 2008/.

5 Documentation of tests

5.1 Limitations

These tests examined the overall conditions present in the clay block – pellet assemblies and evaluated changes in water content as the result of water uptake from a fixed rate-of-supply system. Detailed examination of the water distribution within the volume filled by the clay pellets or individual blocks was not done in Tests 3 through 12 due in large part to difficulties in establishing the mass of water that actually entered the tests (unknown amounts of system leakage). Instead for many of those tests only selective sampling was done to provide a general record of the water distribution within the tests. Later tests (13–24, 27–29) were done in the test chambers after a number of modifications to address leakage issues and so more comprehensive sampling processes were applied. The system leakage identified in a number of the tests resulted in limitations in the ability to analyse the system performance and a number of them were repeated in the modified system.

It should also be noted that these tests were generally of short duration (5 hours to 4 days), and were not intended to provide information on the longer-term behaviour of the system. It is the shorter-term performance of the backfill that water influx will most influence backfilling operations as many metres length of backfill are to be installed each day. The critical period associated with erosion and deformation will therefore be immediately after backfill placement but before a backfilled tunnel section is isolated by a plug or seal. These tests are also not indicative of what will occur during ongoing backfilling operations where interruptions are very brief.

5.2 Documentation prior to start of testing

Prior to the conduct of each test a number of aspects were documented. These included the following:

- Measuring the dimensions of the blocks used to provide a "typical" reference block size.
- Measuring of the outer dimensions of the stack of blocks before the test began.
- Weighing of the mass of clay pellets used to fill the spaces between the blocks and the walls of the test cell.
- Photo-documentation of the test-set-up.

5.3 Documentation during testing

In the course of this test a process of routine visual monitoring and water outflow measurements was followed. This documentation process usually included:

- Photo-documentation as required to record any obvious changes.
- Notes were taken to record observations made.
- Measuring the outer dimensions of the stack of blocks (This was only done at the start of testing and at the time of test dismantling to avoid disturbing the test).
- Collection of water seepage/outflow volumes and recording them.
- Evaluation of erosive activity occurring during test.

5.4 Documentation at termination and during dismantling

At the time of dismantling of the tests a number of records made and samples taken, usually including:

- Photo-documentation.
- Measurement of overall block assembly dimensions.
- Measurement of several blocks to evaluate volume change.
- Careful notation of visual observations made.

5.5 End of test sampling

The basic block geometry used in the conduct of the BACLO Concrete Tube Tests at Äspö during 2006–2007 is shown in Figure 5-1. Four slight variations to this geometry were used due to the need to maintain a minimum 0.1 m gap between the concrete wall and the block assembly. In order to provide a clear recording system during decommissioning of each test, the blocks on face of the block assemblies were assigned numbers that are maintained for all tests.

Many of the tests done as part of this study were of very short duration (~ 5 hours) and had relatively high water inflow associated with them (0.25–1.0 l/min). These tests exhibited considerable variability in the water distribution within the pellets but provided valuable information on system behaviour under high water inflow conditions.

The results of limited end-of-test sampling of several of the earliest tests done where pellets and blocks were both present indicated that important additional information could be collected if the clay sampling done during decommissioning was done in a more systematically than was originally planned. Beginning with Tests 11 and 12 (Figure 5-1), a larger number of samples were taken during test decommissioning in order to gain a more quantitative measure of end-of-test conditions. A sampling plan that captured water content conditions in fixed locations in detail sufficient for analysis, without excessive sampling was developed and tried in decommissioning of these two tests. Based on the experiences in decommissioning of Tests 11 and 12, Tests 15 through 24 were allowed to progress for a longer duration (24 hours–100 hours). With longer testing duration it was expected that water would be more uniformly distributed than in the short (5-hour) tests simply as a result of the time available for homogenization to progress. Figure 5-2 shows the sampling plans for Tests 15 through 24. Additional samples were taken in the course of decommissioning if visual inspection identified unusual features. In order to simplify sampling of the pellet-filled volume, a revised sampling process was developed and implemented. This involved installation of a simple protractor-type measuring device that provided fixed angles and distances for locating sampling points (Figure 5-2).

Sampling of the clay blocks is not done to the level of detail used for the pellet-filled regions, as the primary purpose of this study is to examine the short-term water uptake and transport characteristics of the clay pellets. The water uptake by the blocks is of secondary interest and beyond identifying flow paths between the blocks, absorption of water is not considered to be of particular importance to this study. Additionally, given that the blocks being used are of different (lower) density than is anticipated for use in the filling of a tunnel, water distribution information gathered by detailed sampling of blocks is not particularly applicable. Careful photo documentation of wetting patterns was done and provides much of the information relevant to water uptake and transfer for these tests. Block dimensions were also collected in order to identify what regions have undergone expansion (or compression) as the result of clay pellet swelling. Later long-term (2 to 4 day) tests began to identify issues related to internal erosion of the block materials and the impact of this is discussed later in this document.

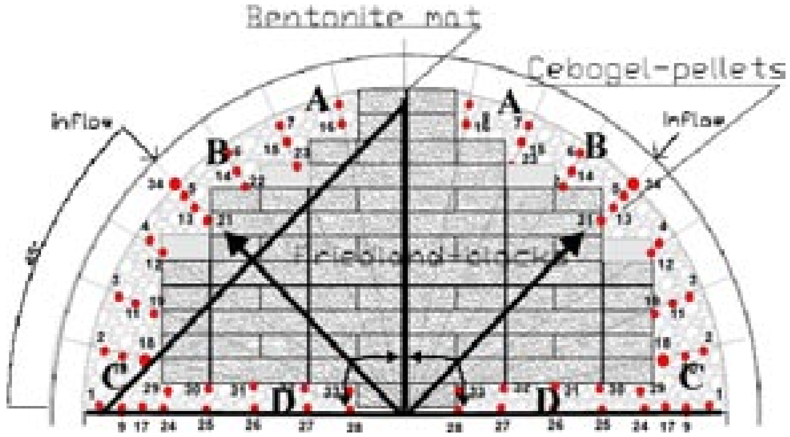


Figure 5-1. *Sampling plan for Tests 13–14.*

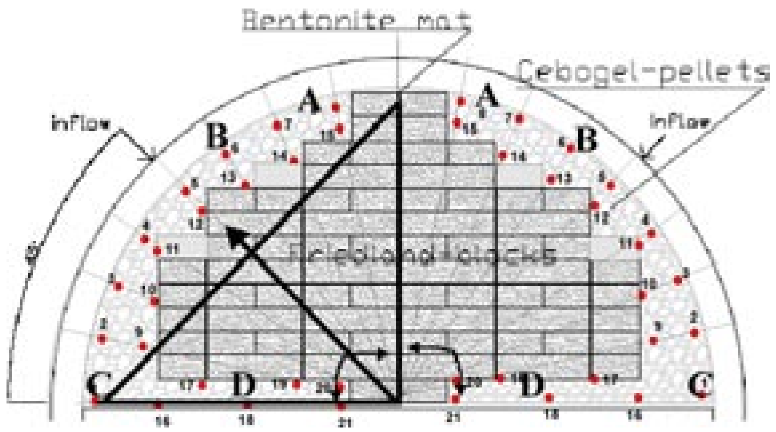


Figure 5-2. *Sampling plan for Tests 15–24, 27–29*. (Note: tests 21–24 and 27–28 had the second layer from floor deleted reducing the number of blocks from 184 to 164 for these tests).*

6 Summary of test results

The tests completed as part of this study of the behaviour of water entering a simulated section of tunnel that had previously been backfilled are described and discussed in detail in Appendix A of this report. In Chapter 6 the key results are briefly summarized and briefly discussed with reference to their significance to a backfilled section of tunnel. It should be noted that much of the information collected in this study is most applicable to a situation where for whatever reason, unanticipated interruption of backfilling operations occurred. The backfilled section, left unattended or where installation of further materials was not possible would then be potentially subject to a period of time (several days to a week) without maintenance. During this time water would continue to enter the already backfilled section of tunnel. Ultimately this inflowing water will make its way towards the downstream face of the backfilled tunnel. The time required for this water to exit the backfill and the manner in which it exits are critical factors in determining the influence of seepage on the backfill and what remediation may be necessary once backfilling operations recommence.

These tests also provide valuable information regarding the manner in which a piping or channelling feature developed a distance away from the working face will interact with a newly backfilled section of tunnel. The time required for such a feature to make its way into or through a newly backfilled section of tunnel will provide guidance regarding the rate of backfilling necessary to stay ahead of water influx or conversely, what the limits on the rate of inflow (or channelled flow) into a channel in the backfill are in order to ensure that backfilling operations can stay ahead of the wetting front.

These tests do not take into account the operational aspects of backfilling, where a section of tunnel has blocks installed and then at some point soon thereafter, pellet filling materials are installed. This means that water may be entering the as-yet unfilled perimeter of the backfilled tunnel, potentially impacting the ability of the subsequently installed pellet materials to delay water movement along the tunnel perimeter. These types of interactions can only be effectively studied in simulations done at larger scale.

For the purpose of providing a focussed discussion on the results obtained, Chapter 6 contains only a brief summary of the key observations and measurements. This discussion is complemented by photographs/distribution plots showing the distribution of water at the time of dismantling. Additionally, each test has a schematic produced that illustrates how water would have moved into systems having the geometry of a KBS-3V emplacement tunnel.

Detailed documentation associated with these tests are provided in Appendix A and so only a brief summary of the performance of each test is provided below. Table 6-1 and Table 6-2 summarize the conditions imposed and some of the key observations made during testing.

6.1 Block assemblies lacking pellet fill

The first two tests of this series involved installation of block assemblies without subsequent filling of the space between the blocks and the tube walls with pellet materials. These tests were done to examine the extreme situations of:

1. A very dry tunnel section where there is no inflow of water from the surrounding rock and the block-filled region is left unattended and exposed to the naturally high humidity commonly found underground.
2. A tunnel section where there are small, localized features that can supply a small quantity of water the the surface of the blocks through dripping. This type of feature can also be found in an Äspö-type environment. However, in the case simulated here, the blocks had been installed on a granular bentonite bed but for some reason subsequent installation of pellet materials did not occur in a timely manner.

6.1.1 Test 1: No inflow, only natural humidity of an open tunnel

The block assembly shown in Figure 6-1 was left undisturbed for 38 days in a tunnel at the 420 m level at Äspö. No liquid water was allowed to contact the blocks and at the end of the test the assembly was carefully measured and then dismantled to determine what changes had occurred in the blocks. The overall density of the blocks decreased approximately 6% and the overall volume change in the assembly was approximately 2% (expansion). The assembly therefore experienced a slight increase in volume and reduction in dry density as a result of water uptake from the atmosphere. There were minor surface disruptions (cracks) on those blocks on the outside of the assembly, attributed to the uptake of water from the atmosphere; they did not however adversely affect the stability of the assembly. It is unlikely that the small changes observed in the system would adversely affect the system behaviour should it subsequently have pellets installed. A more detailed description of the test is provided in Appendix A.

6.1.2 Test 2: 0.1 l/min inflow onto surface of blocks lacking pellet cover

The same type of block assembly as was used in Test 1 was installed in the same environment as in Test 1, excepting that in this case water was supplied at a rate of 0.01 l/min via a drip hose located above the top of the assembly. This was intended to simulate a situation where a block assembly was unavoidably left partially constructed (no pellet fill between rock and blocks) for a substantial period of time. As can be seen in Figure 6-2 the result of this influx was physical disruption of the block assembly.

It is evident from this test that the blocks cannot withstand substantial water influx before a protective and supporting pellet-fill material is installed. A detailed description of this test and its subsequent dismantling and sampling is provided in Appendix A of this report.

Figure 6-1. *As-Built Test #1.*

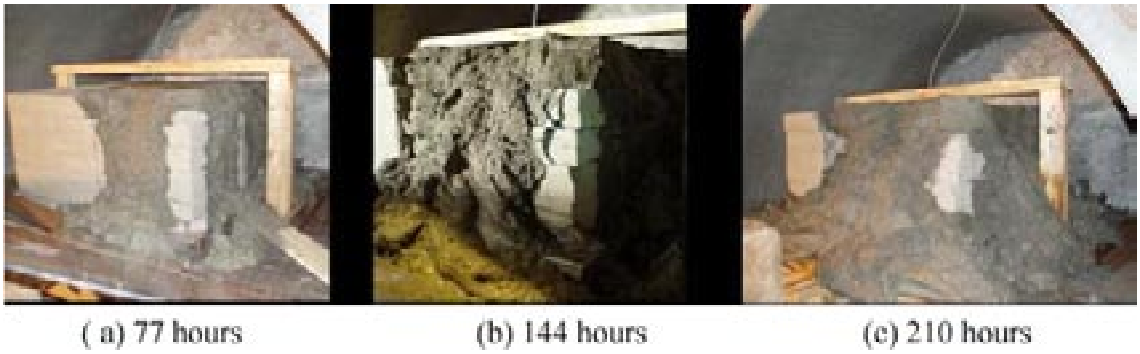


Figure 6-2. *Progressive failure of block assembly at 77, 144 and 210 hours.*

6.2 Block assemblies having pellet fill surrounding them

6.2.1 Tests 3 and 4: 0.1 l/min supplied at test mid-height

Tests 3 and 4 operated for 46.5 hours with water being supplied at the pellet-concrete interface at the mid-height of these assemblies, at 0.6 m distance from the front face. Figure 6-3 shows the front face of these tests at the time of dismantling. Water exited these assemblies at approximately the same time, beginning about 130 minutes after the start of water inflow, but outflow was not measurable until about 24 hours into the test. Water was observed to exit along the horizontal contacts between the pellets and the blocks, the elevation rising with increasing time. By the end of testing, the pellet-fill, excepting the lowermost regions underneath the blocks was largely saturated. At that time almost all the water entering these tests was rapidly transiting the system although very little water had entered the block-filled regions and there was little evidence of substantial ongoing wetting at the end of the test, as can be seen in Figure 6-3

These tests showed little resistance to water inflow. A detailed presentation of the data associated with these tests is provided in Appendix A and is included in the overall analyses in Chapter 7 and brief summaries of the key findings are provided in Table 6-1 and Table 6-2. Figure 6-4 shows simplified diagrams of the water inflow patterns into and through these tests.

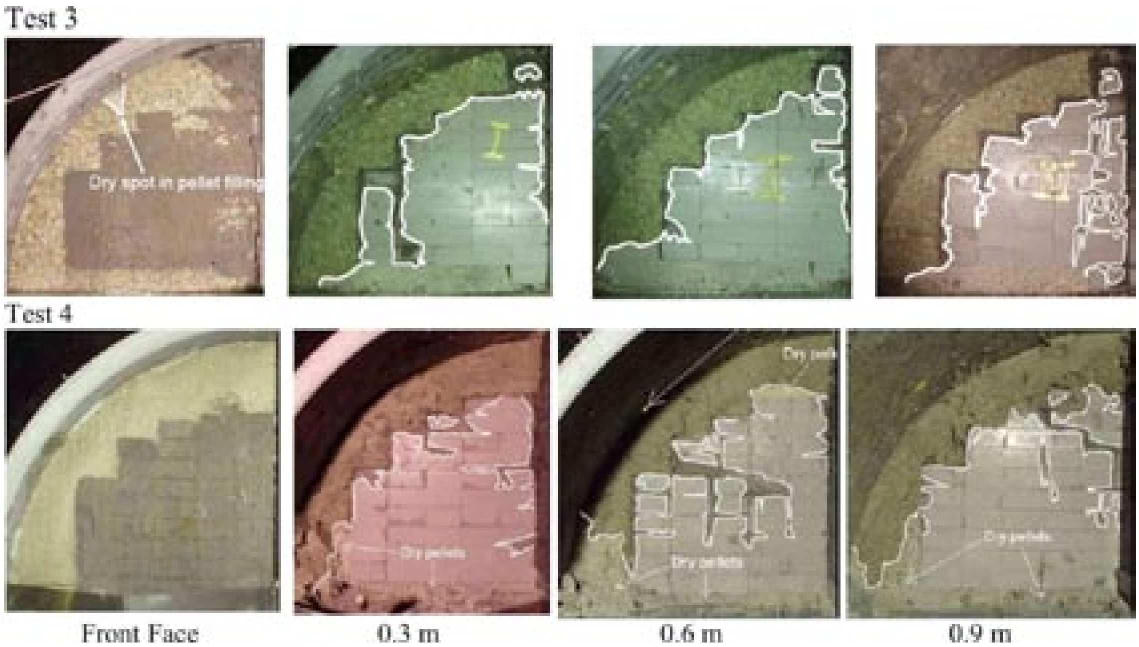


Figure 6-3. Wetting of Tests 3 and 4 (0.1 l/min inflow for 2 days).

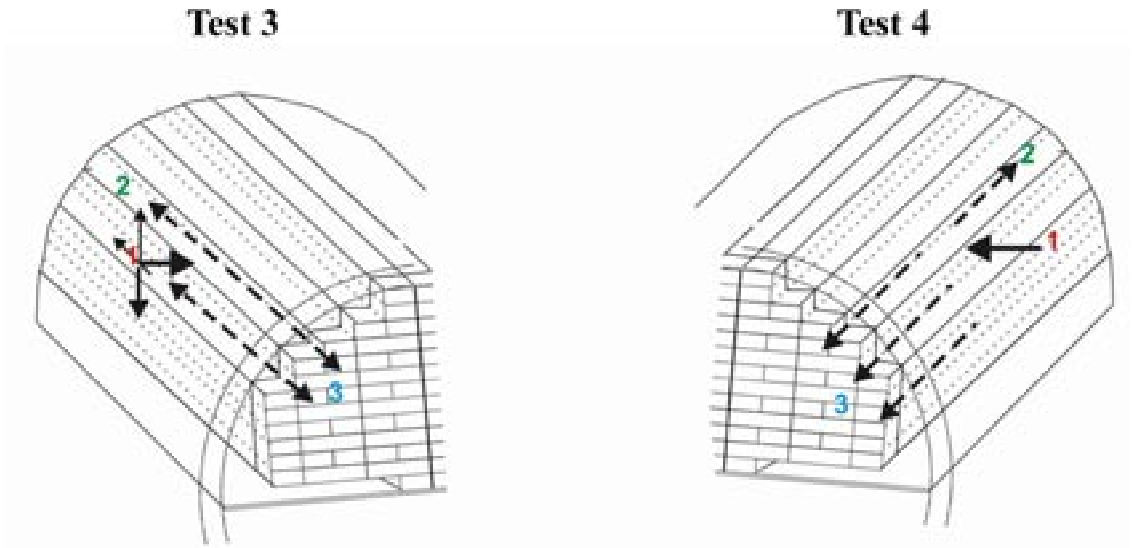


Figure 6-4. Schematic showing estimated water pathways in Test 3 and 4. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.

6.2.2 Tests 5 and 6: 1.0 and 0.25 l/min supplied at test mid-height

Test 5 and Test 6 were supplied with 1 and 0.25 l/min water respectively for a period of only 5 hours before they were ended.

Water began exiting Test 5 within 8 minutes of the test starting and after 5 hours the pellet-filled volume was largely saturated and 50% of the inflowing water was exiting the test via flow along the phreatic surface and along the block-pellet interface. The wetted portions of the assembly can be seen in Figure 6-5. There was little resistance to water movement into and through this test for the entire period of its operation. Detailed discussion of the test is provided in Appendix A and in Chapter 7, while brief summaries of the key observations and measurements are provided in Table 6-1 and Table 6-2. A schematic describing the evolution of water movement into and through this test is provided in Figure 6-6.

Test 6 had water exiting it within 2 hours of the start of wetting, it exited via the phreatic surface of the clay pellets and also along the horizontal contacts between the pellets and the clay blocks, as can be seen in Figure 6-6. The short duration and relatively low inflow rate of this test meant that hydration had not substantially progressed at the time of its termination and so only a small proportion (12%) of the inflowing water was exiting the system. Figure 6-7 shows a simplified schematic representation of the evolution of water flow into the test. The details of this test and its evolution are provided in Appendix A and evaluated in Chapter 7.

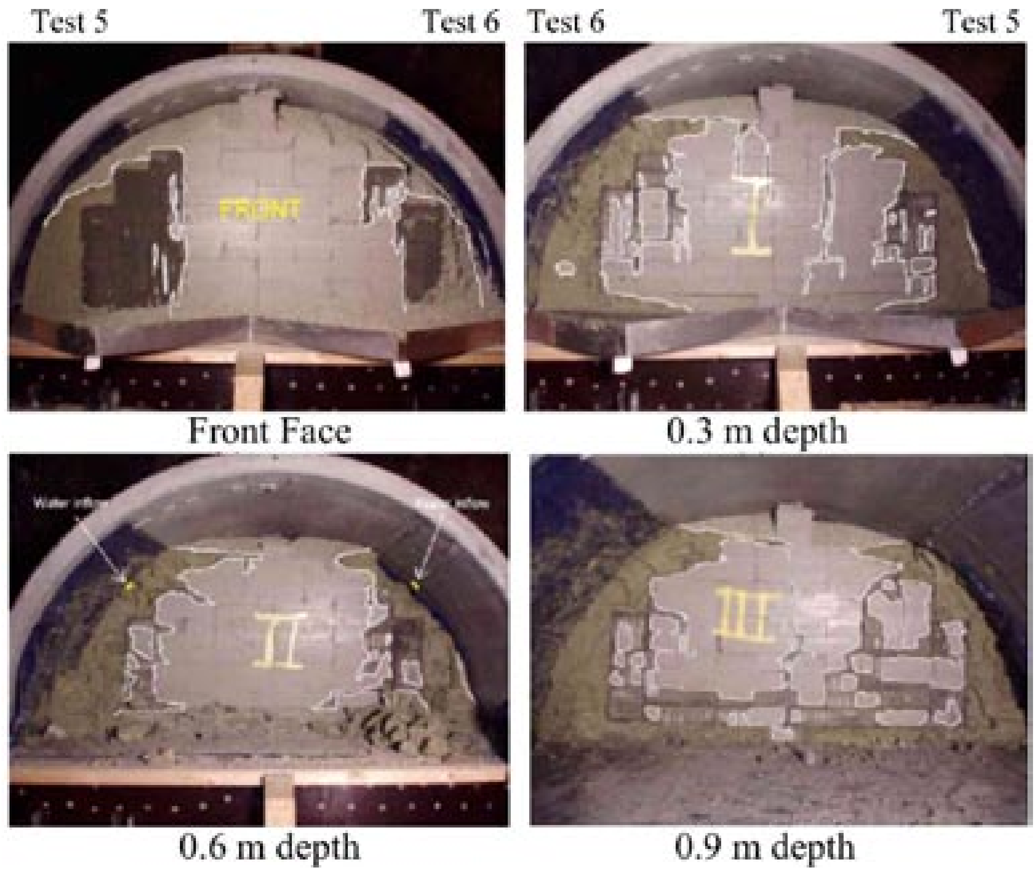


Figure 6-5. *Wetting of Tests 5 and 6 (1.0 l/min and 0.25 l/min for 4.5 hrs) (note extensive wetting of pellet fill excepting at crown of assembly and limited wetting of blocks due to rapid inflow and through flow of water).*

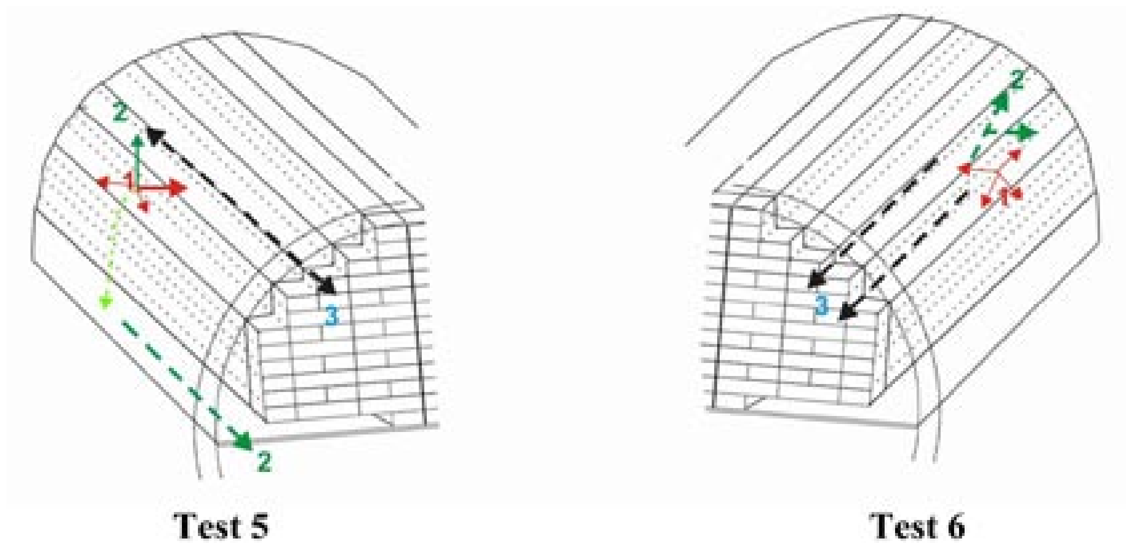


Figure 6-6. *Schematic showing estimated water movement pathways in Tests 5 and 6. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

6.2.3 Tests 7 and 8: 0.01 and 0.03 l/min supplied at test mid-height

Test 7 and Test 8 were supplied with 0.01 and 0.03 l/min water respectively for a period of almost 5 days before they were ended.

Water did not exit Test 7 in the course of its conduct. Resistance to inflow was relatively low but gradually increased with time as the tests took on water, reaching approximately 60 kPa. The wetting pattern within the test at the time of dismantling is provided in Figure 6-8, a simplified water movement diagram in Figure 6-10 and the results are discussed in detail in Appendix A. The significance of the observations with regards to the behaviour of a backfilled section of tunnel is evaluated in Chapter 7.

Test 8 saw water exit the backfilled volume after 50 hours of operation, with flow occurred at several locations including the pellet-chamber interface and along the horizontal interfaces between the pellets and the clay blocks as can be seen in Figure 6-9. There was little resistance to water movement into and through this test with a very similar inflow resistance to that observed in the adjacent Test 8 (~60 kPa at the end of the test). Figure 6-10 shows the generalized inflow patterns for this test. Detailed discussion and assessment of the test is provided in Appendix A and Chapter 7.

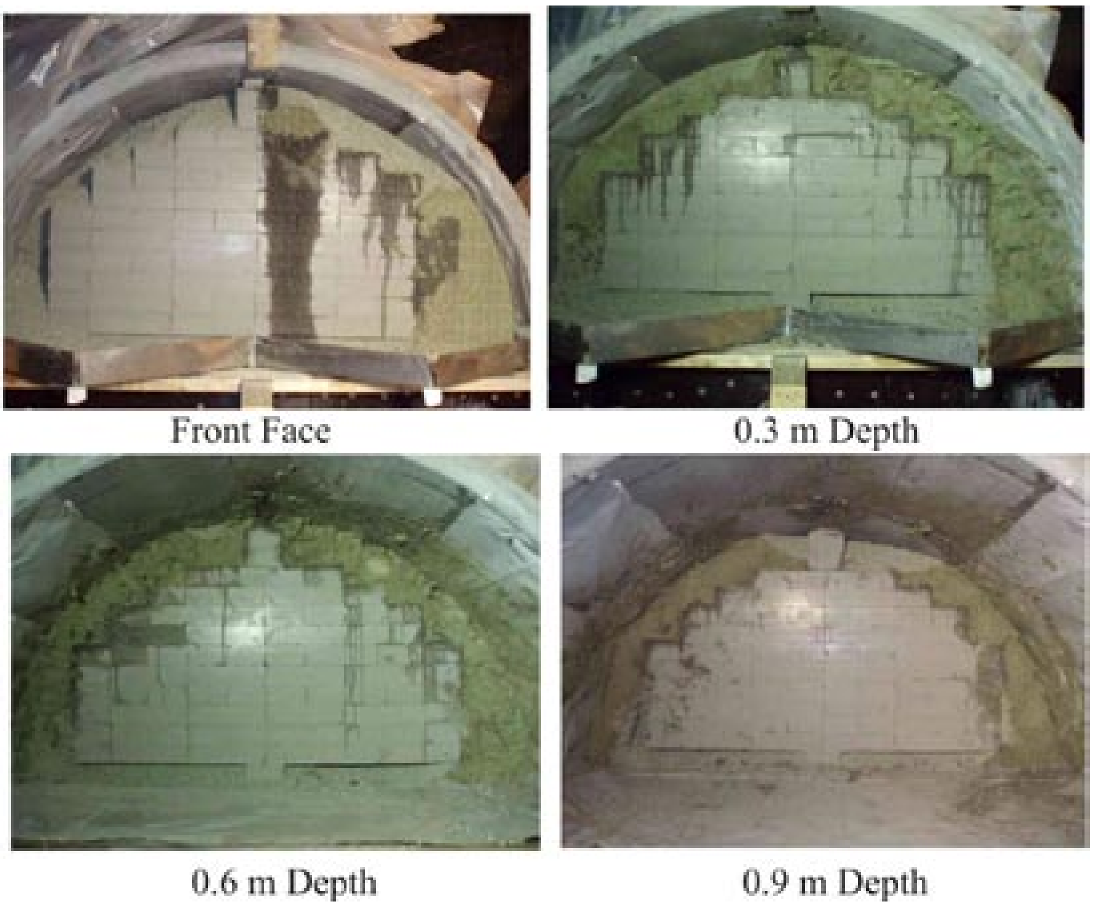


Figure 6-7. *Water distribution in Tests 7 and 8 (0.01 and 0.03 l/min for 5 days). (Note the high degree of pellet-only wetting excepting in floor and crown regions).*

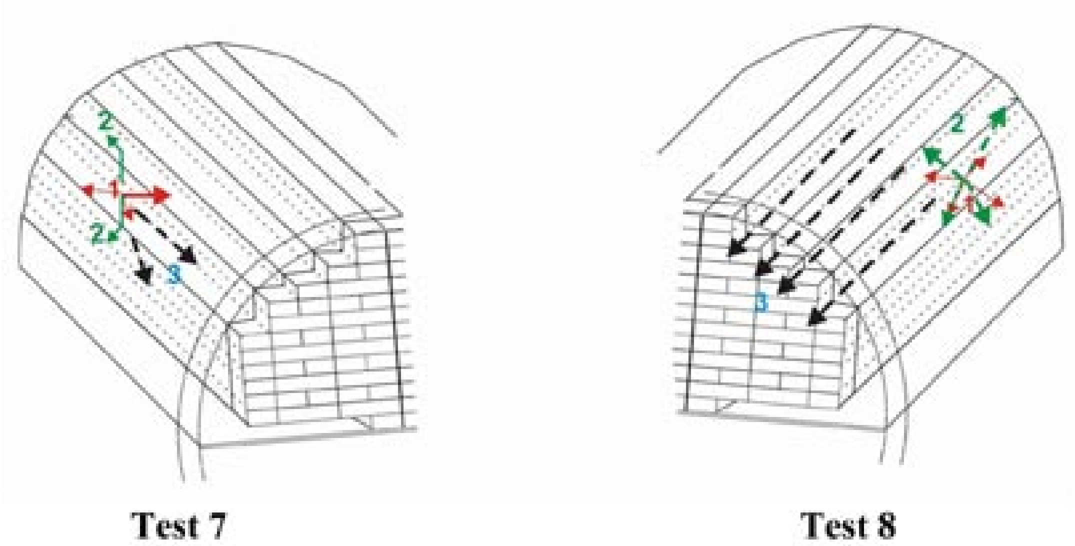


Figure 6-8. *Schematic showing estimated water movement pathways in Tests 7 and 8. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

6.2.4 Tests 9 and 10: 0.1 and 0.25 l/min supplied at test mid-height

Test 9 and Test 10 were supplied with 1 and 0.25 l/min water respectively for a period of only 24 and 5.5 hours respectively before they were ended.

Just prior to completion of the test, water was observed to be exiting the pellet and block assembly from the horizontal contacts between the pellets and blocks on the outermost stacks of blocks as can be seen in Figure 6-9. Although exiting the test there was insufficient time between water arriving at the face and termination of the test for any fluid to reach the collection system or for material to be eroded from the test. The interpreted general inflow pattern for this test is provided in Figure 6-10. The maximum resistance to water inflow was only 20 kPa. Water movement into this test and its behaviour are discussed in detail in Appendix A and Section 7 and key measurements and observations are provided in Tables 6-1 and 6-2.

Test 10 was a replicate of Test 8, excepting that there were 5-mm-wide vertical joints intentionally installed within this test and operated for only 5.5 hours. Water exiting it 3 hours into its operation (30 litres entry) with 15 litres ultimately exiting before the end of testing. Flow first occurred in the lower outside corner of the test at the junction of the floor, concrete and pellets. An hour later outflow began on the lowermost horizontal interface between the clay blocks and pellets. Figure 6-9 shows these outflow locations and Figure 6-10 shows the interpreted water movement into and past the backfill. This material exhibited essentially no resistance to water inflow, developing only 14 kPa resistance over the 5.5 hours of its operation. Detailed discussion of the test and its operation are provided in Appendix A and its significance to overall backfill behaviour is discussed in Section 7. Tables 6-1 and 6-2 provide a summary of the key observations and measurements collected in this test.

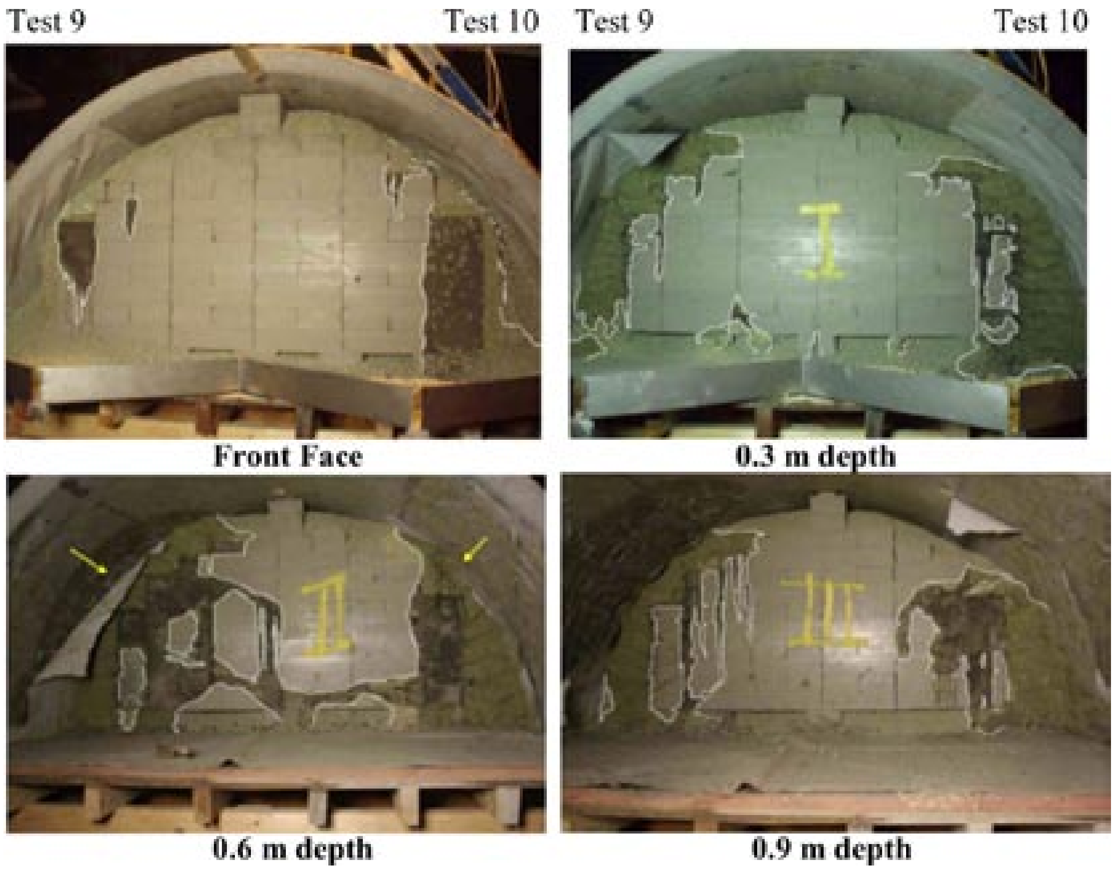


Figure 6-9. *Water distribution in Tests 9 and 10 (0.01 and 0.03 l/min for 5 days).*

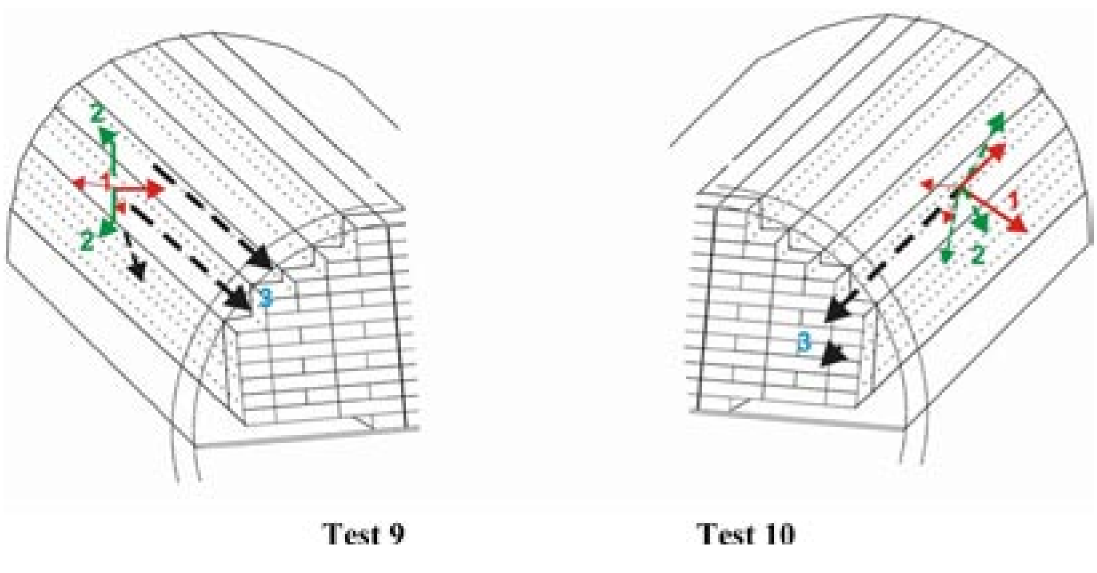


Figure 6-10. *Schematic showing estimated water movement in Tests 9 and 10. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

6.2.5 Tests 11 and 12: 0.1 and 0.25 l/min supplied at test mid-height

Test 11 and Test 12 were supplied with 0.1 and 0.25 l/min water respectively for 24 and 5.5 hours respectively.

Water exited Test 11 between 3 and 13 hours after the start of water inflow. Resistance to inflow was relatively low but was gradually increasing with time as the tests took on water, reaching approximately 45 kPa after 24 hours. The wetting pattern within the test at the time of dismantling is provided in Figure 6-11, a simplified water movement diagram in Figure 6-12 and the results are discussed in detail in Appendix A. The key measurements and observations made in the course of testing are presented in Tables 6-1 and 6-2. The significance of these observations with regards to the behaviour of a backfilled section of tunnel is assessed in Chapter 7.

Test 12 saw water exit its downstream face after 1.5 h of operation. Resistance to inflow was gradually increasing but after 5.5 hours had only risen to 22 kPa. The pattern of water uptake at the time of test dismantling 18 h after the supply of water was turned off is presented in Figure 6-11 and a simplified water movement diagram is provided in Figure 6-12. A summary of the key measurements is provided in Tables 6-1 and 6-2. The significance of the observations and measurements made in the course of testing are discussed in Chapter 7 with detailed presentation of the test conduct and behaviour presented in Appendix A.

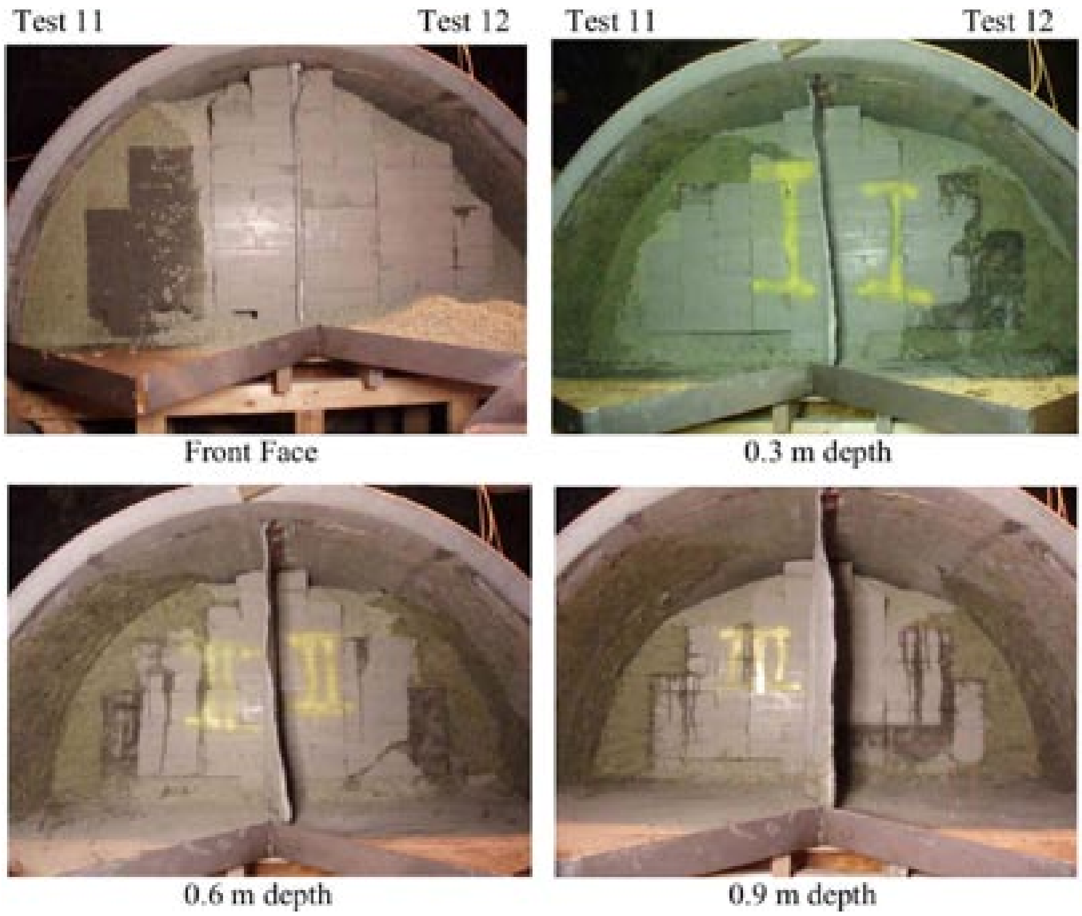


Figure 6-11. *Water distribution in Tests 11 and 12 (0.1 for 24 h, 0.25 l/min for 5.5h). (Note lack of wetting below block assemblies and limited water movement into blocks).*

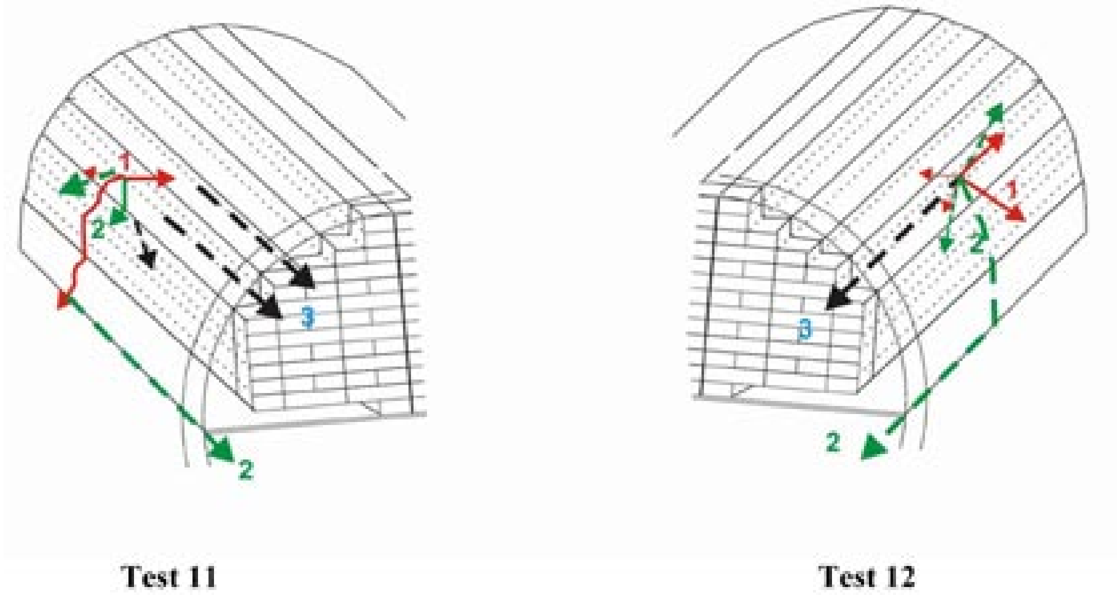


Figure 6-12. Schematic showing estimated water movement pathways in Tests 11 and 12. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.

6.2.6 Tests 13 and 14: 0.5 and 0.25 l/min supplied at test mid-height

Tests 13 and 14 operated for only 5 hours before being dismantled. They therefore show the very early stages of water ingress and movement through and around a block and pellet backfill system.

Test 13 had water exit its downstream face after only 45 minutes of test operation. Figure 6-13 shows the measured water contents for this test with darker zones having the highest water content. There was clearly extensive water uptake in the rear-most portions of this test with wetting progressing towards the front face via the horizontal pellet-block and pellet-concrete interfaces. The water movements associated with this type of wetting are shown schematically in Figure 6-14. The detailed observations and measurements made in the course of this test are provided in Appendix A and are discussed with reference to their significance to overall backfill behaviour in Chapter 7. A brief summary of the key measurements and results are provided in Tables 6-1 and 6-2.

Test 14 had water outflow begin just prior to discontinuation of water inflow after 5 hours and initiation of dismantling. Figure 6-13 shows the more limited degree of wetting that has occurred in this test and the tendency for greater wetting along pellet-block and pellet-concrete interfaces near the inflow location are illustrated in Figure 6-14. A more detailed discussion of the evolution of this test is provided in Appendix A and the significance of the results are discussed in Chapter 7.

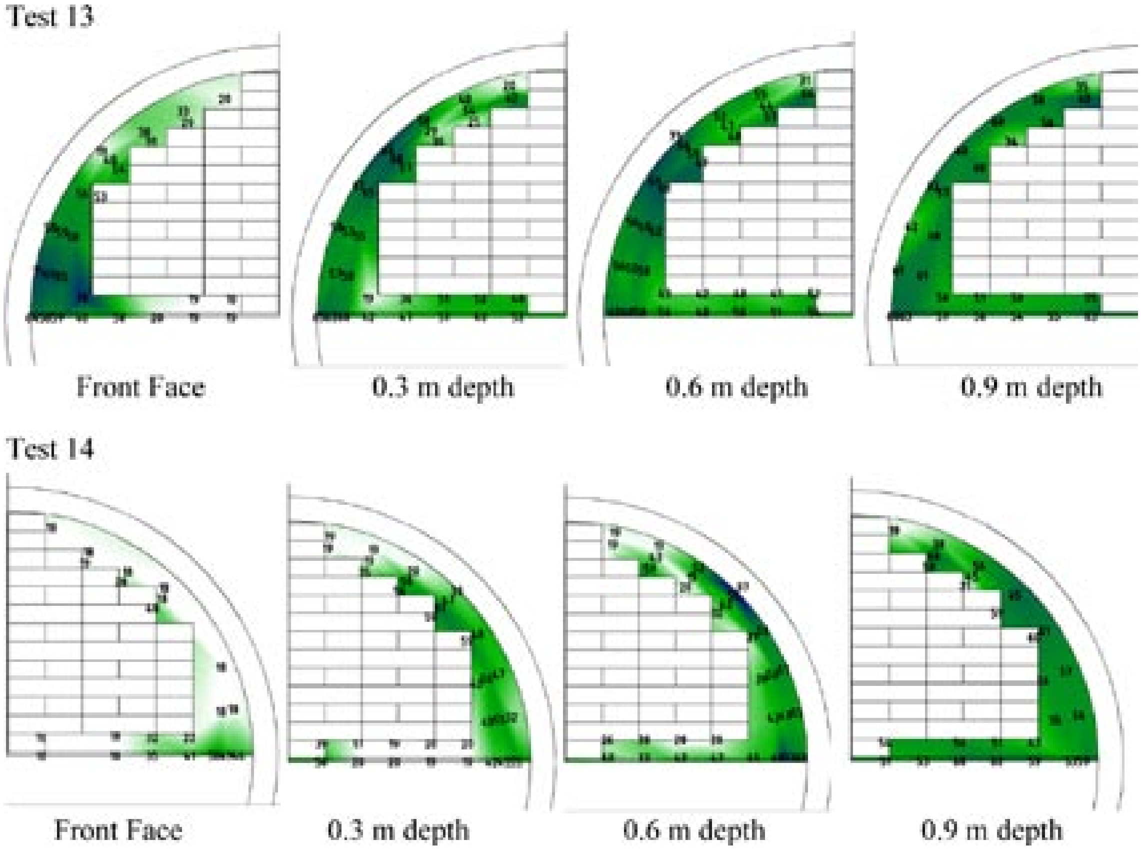


Figure 6-13. Water distribution at end of testing: Tests 13 and 14.

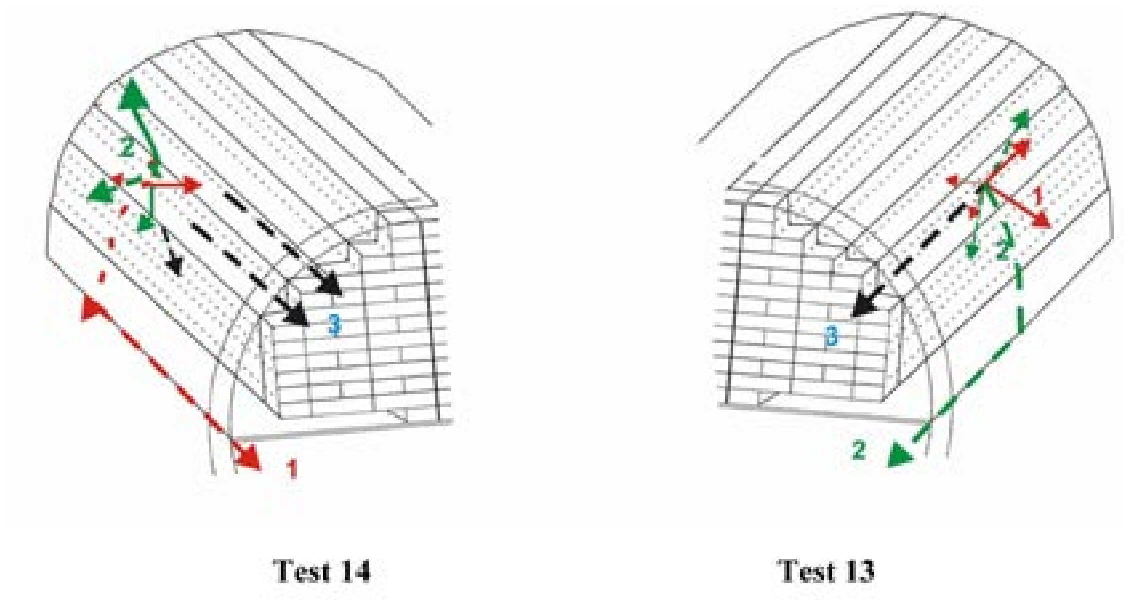


Figure 6-14. Schematic showing estimated water movement in Tests 13 and 14. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.

6.2.7 Tests 15 and 16: 0.1 and 0.25 l/min supplied at test mid-height

Tests 15 and 16 were each operated for 24 hours with water entering at a single location at the cell mid-height.

Test 15 had 0.1 l/min supplied to it and operated as designed, with no leakage from the supply system. Monitoring of inflow resistance, outflow rate and erosion were successful, providing valuable information regarding system evolution. This test experienced first outflow only 6 hours into the test but outflow was not sustained, at the time of test completion only 3.8 litres had exiting the system. The remainder of the inflow was absorbed into the matrix of the test, or was accumulating in the crown regions towards the rear of the assembly. Inflow resistance was low in this test, although it was not as variable as observed in other tests done at similar inflow rate. Figure 6-15 shows how water was being directed upwards at the inflow point, beginning to develop a very wet volume of pellets near the chamber crown with wetting beginning to extend towards the front face of the assembly. The test did not however operate long enough for the crown region to become a pathway for water flow out of the assembly. A detailed assessment of the observations made during test observation is provided in Appendix A and is summarized in Chapter 7.

Test 16 had 0.25 l/min supplied to it and experienced water outflow 6 hours and 20 minutes (95 litres inflow) into the test. Initial outflow occurred along the 3 horizontal surfaces where the blocks and pellets are in contact. Within 5 minutes of outflow starting, flow was observed to be exiting the joint near the crown of the assembly and this rapidly established itself as the primary flow path for exiting water. This location was associated with the Friedland clay blocks and considerable erosion was observed in the remaining 18 hours of testing. Inflow resistance gradually increased during operation of the test although the magnitude was not different that other tests done as part of this study. A detailed assessment of the observations made during test observation is provided in Appendix A and is discussed with regards to overall system operation in Chapter 7.

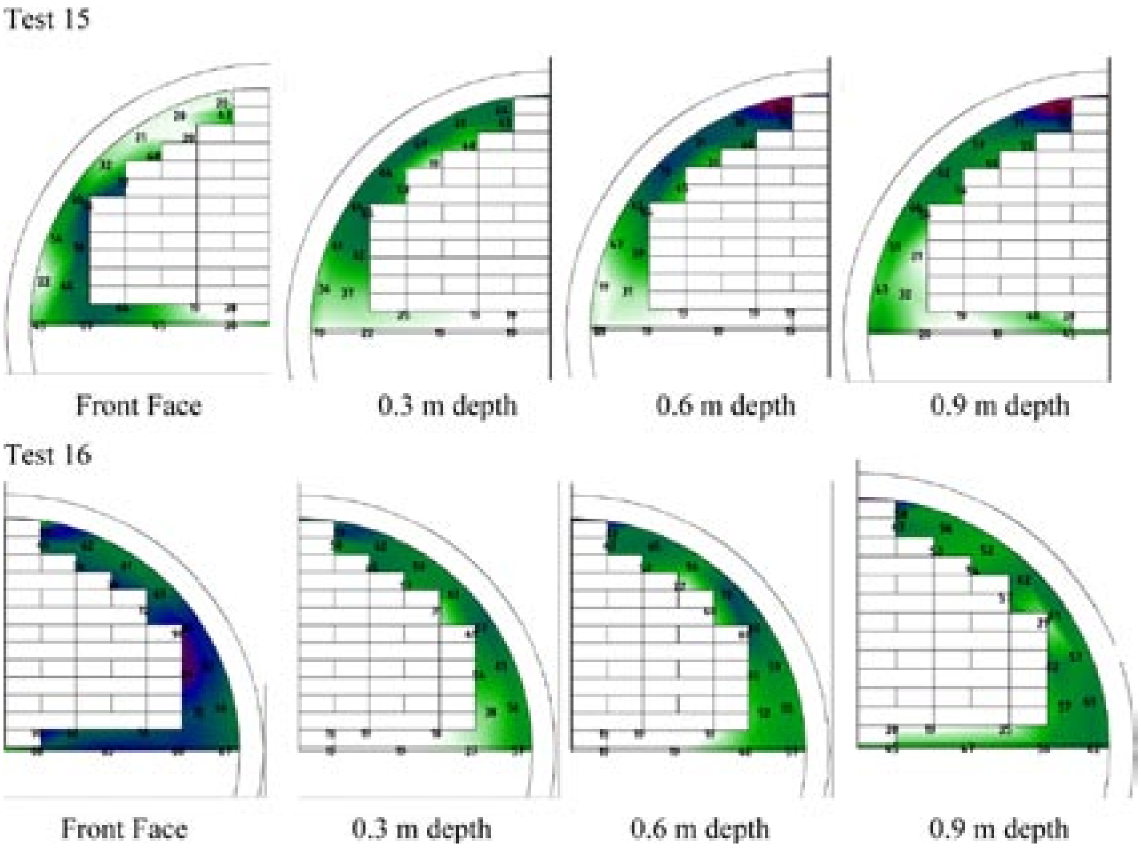


Figure 6-15. Water distribution at end of testing: Tests 15 and 16.

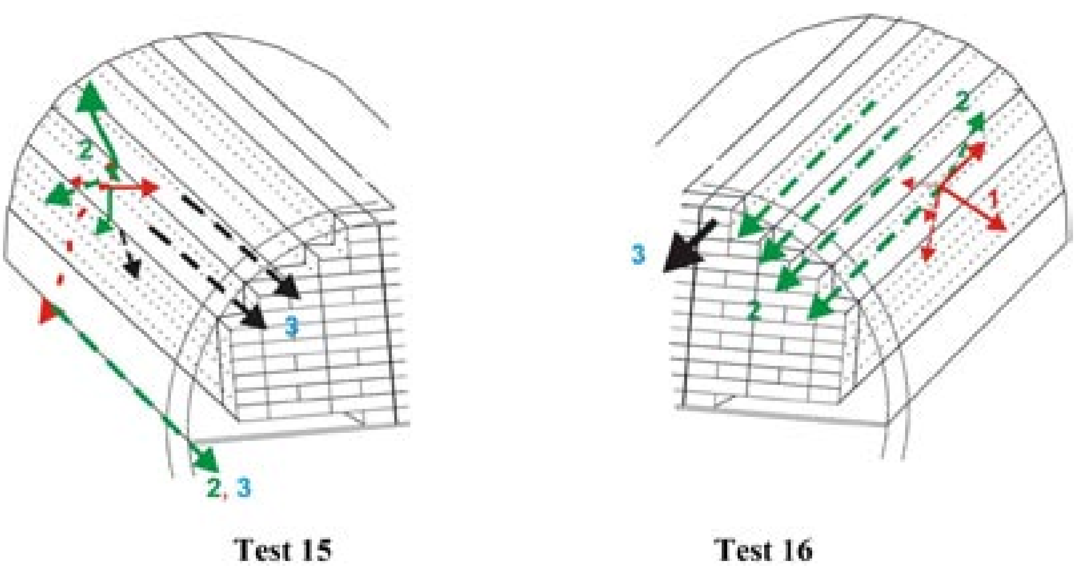


Figure 6-16. Schematic showing estimated water movement in Tests 15 and 16. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.

6.2.8 Tests 17 and 18: 0.1 and 0.25 l/min supplied at test mid-height

Test 17 was supplied with 0.08 l/min for a period of 48 hours. Water began to exit the front face of Test 17 after approximately 2 hours and 50 minutes of test operation via a vertical joint between the outermost blocks. This was likely the result of water moving along the horizontal pellet-block contact until it found a small vertical passage. This pathway through the blocks persisted and resulted in substantial erosion. Water movement was dominated by the internal flowpath but movement along the other horizontal contacts between the pellets and blocks was also evident, as can be seen in Figure 6-17. Test 17 exhibited a relatively smooth and rapid development of its inflow resistance; the peak resistance was achieved after about 24 hours after which it stabilized. The magnitude of inflow resistance was not however discernibly different than other tests done at this inflow rate. A schematic showing the manner in which water entered and moved through this test is provided in Figure 6-18. Detailed presentation and discussion of the test results is provided in Appendix A and its significance is assessed in Chapter 7.

Test 18 was supplied with 0.25 l/min for 48 hours. Water began to exit the front of the assembly after only 70 minutes of operation, exiting the test from the lower corner where the floor, concrete tube and pellets intersect (Figure 6-17). This location continued to produce a limited amount of outflow for most of the test's duration but had very little eroded material associated with it. After 7 hours into the test water was exiting the system at the lowermost horizontal contact between the clay blocks and the pellet materials. After 24 hours outflow was dominated by a single point located near the top of the test, just above the last horizontal layer of blocks (see Figure 6-17). This was nearly the identical location where channelling flow was observed in Test 16 (0.25 l/min for 24 hours) and considerable erosion of block materials was observed. Figure 6-18 provides a schematic showing the movement of water into this test. The resistance measured is essentially identical to that observed for Test 16 during its 24 hours of operation, gradually increasing towards an equilibrium value of approximately 80 kPa until approximately 40 hours into the test when a very marked drop in inflow resistance occurred (from 80 kPa to 50 kPa). This is likely associated with further development of the main flow channel. Details of the test are provided in Appendix A and the overall system behaviour is discussed in Chapter 7.

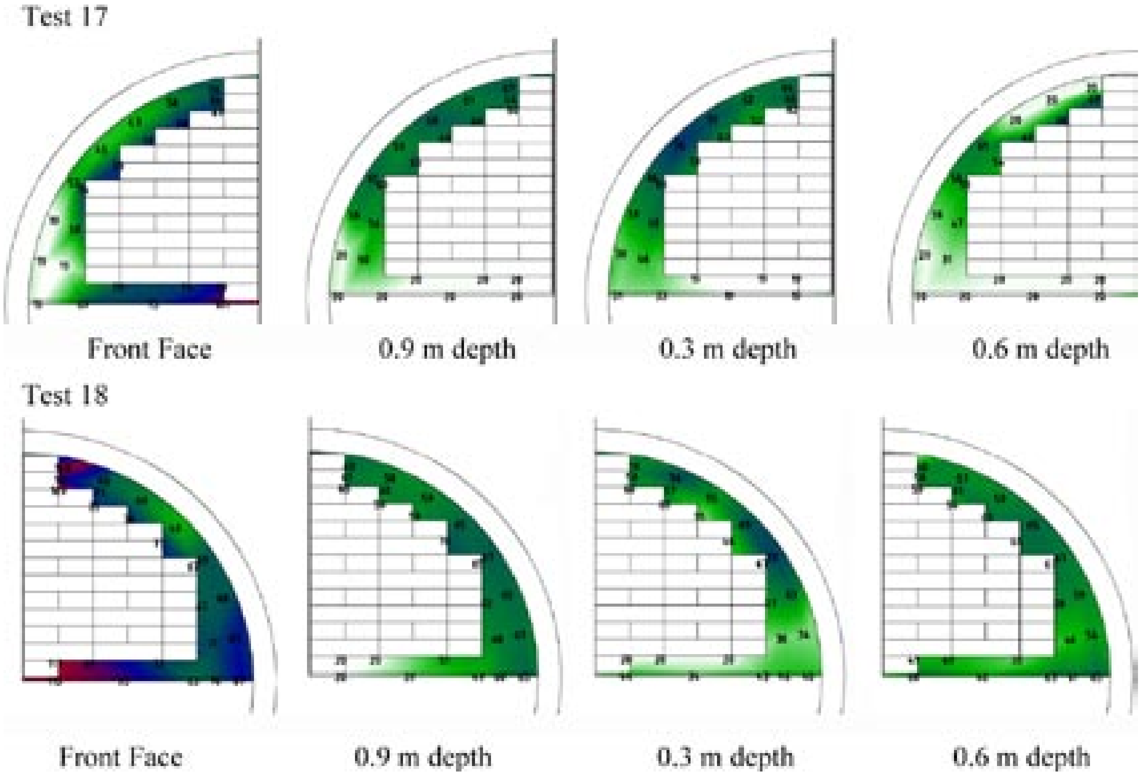


Figure 6-17. *Water distribution at end of testing: Tests 17 and 18.*

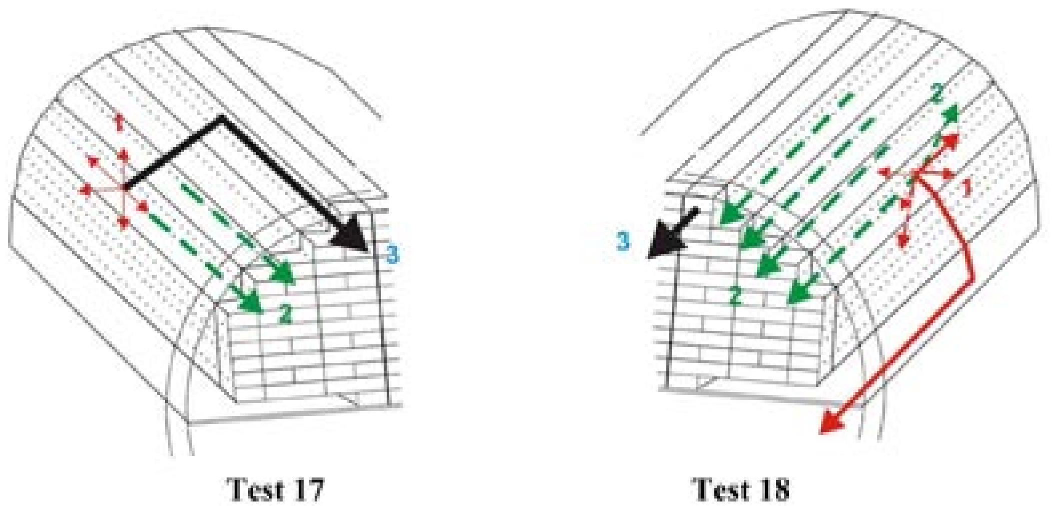


Figure 6-18. *Schematic showing estimated water movement in Tests 17 and 18. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

6.2.9 Tests 19 and 20: 0.1 and 0.5 l/min supplied at test mid-height

Test 19 operated at 0.1 l/min for a period of 4 days. Water began to exit the front face after 5 hours, via the horizontal contact between the clay blocks and the pellet materials. By the end of 24 hours of operation, outflow was established at two distinct locations, one at the concrete-pellet interface in the upper regions to the test cell and the other at the pellet-block interface near the top of the test assembly (Figure 6-19). The uppermost feature was associated with a clear piping feature that extended several centimetres into the blocks and considerable erosion of block material was associated with this pipe. Figure 6-20 provides a schematic of the water movement in this test. The resistance to inflow was variable with 10 kPa fluctuations evident for much of the test's operation. An average resistance of 80 kPa was established by the end of the first day of test operation, the same time as the establishment of the flow paths that persisted for the remaining 3 days of test operation.

Test 20 operated at 0.5 l/min inflow for 4 days. A total of 3 m^3 was injected into this test and it represents the longest duration test where high inflow was applied. Water was observed exiting the test chamber after 160 minutes of operation, at which time only 80 litres of water had entered the system. Initial outflow occurred at the contact between the floor, concrete wall and pellets but this flowpath was not stable with numerous changes in the location of water outflow occurring during the course testing. Within 24 hours of starting the test a stable flow path had developed and remained for the rest of the test. This pathway was unusual in that it was located at the base of the clay block assembly at its contact with the clay pellets and obviously represents a flow path that passes through the block assembly.

Resistance to inflow in Test 20 was variable with a trend towards lower resistance with time (and development of erosion-related flowpaths). Figure 6-19 shows the erosive flow paths developed in this test and Figure 6-20 shows the manner in which water entered and passed through the assembly. Test 20 experienced the highest amount of flow-induced erosion observed in this study and highlights the potential problems of installing backfill in a high-inflow region and also the relative ease with which Friedland clay can be removed if an internal flow path is developed. Details of the evolution of this test, erosion and overall behaviour are provided in Appendix A and are discussed in Chapter 7.

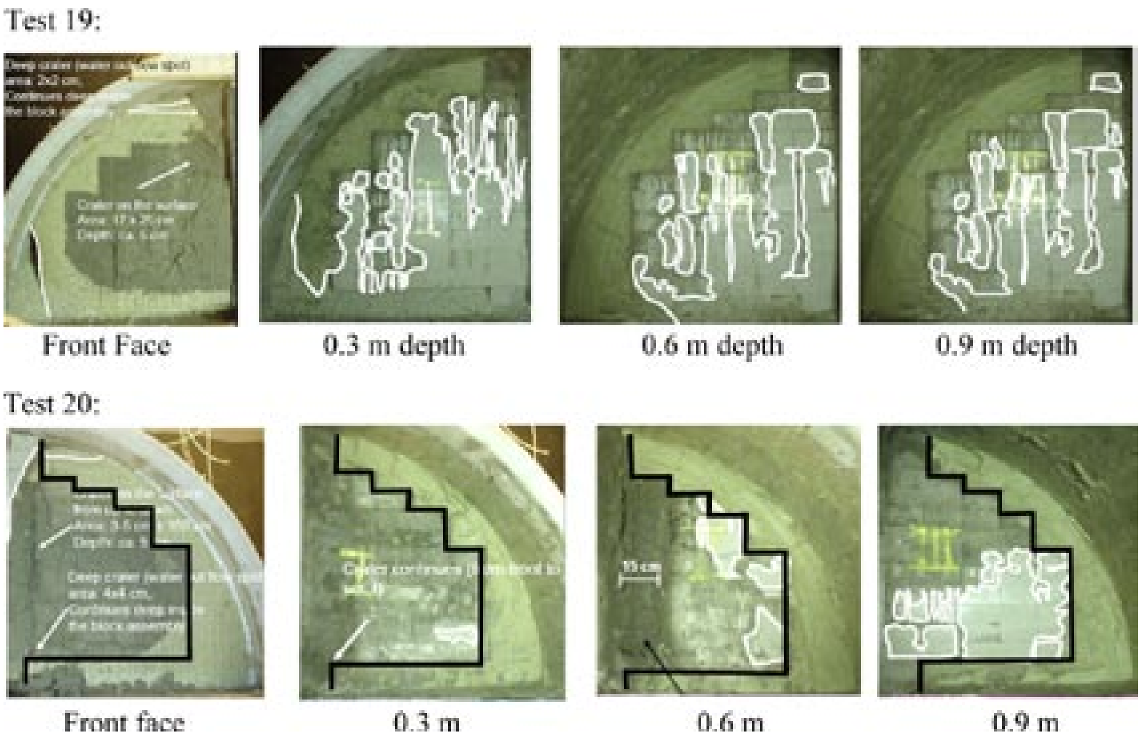


Figure 6-19. Water distribution at end of test: Tests 19 and 20.

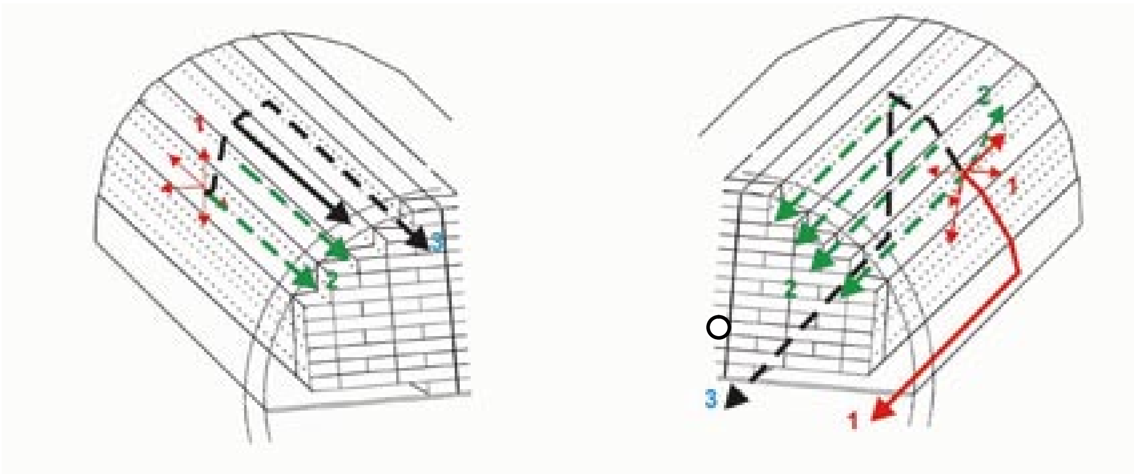


Figure 6-20. *Schematic showing estimated water movement in Tests 19 and 20. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

6.2.10 Tests 21 and 22: 0.1 and 0.25 l/min supplied at test mid-height

Test 21 operated at 0.08 l/min for a period of 48 hours. It differed from most of the other tests done in the course of this study in that instead of Cebogel pellet material between the blocks and the concrete tube, the annular space was filled with granulated Minelco bentonite. Water began to exit the assembly between 8 and 24 hours of operation and before 24 hours had elapsed. By 24 hours the test was exhibiting considerable water outflow at the horizontal interfaces between the blocks and clay granules at the uppermost layer of blocks. The location of outflow changed gradually and by 30 hours outflow was restricted to three points near the crown of the test at the pellet-concrete tube interface. Resistance to water inflow increased gradually over the course of testing but by 48 hours had only reached about 50 kPa. Although considerable water outflow occurred via piping features along the crown of the assembly, the water exiting the granule-concrete interface of Test 21 was clear and contained very little eroded material. Figure 6-21 shows this preferential wetting of the crown region and the very isolated nature of the wetting that has occurred. Figure 6-22 shows a schematic of the path taken by the water entering the system. Details of the operation and behaviour of this test are provided in Appendix A and the results are discussed in Chapter 7.

Test 22 operated at an inflow rate of 0.25 l/min for 48 hours and like Test 21 involved use of Minelco granulated bentonite rather than pellets. Water began exiting the assembly after 4–5 hours of inflow, at the pellet-concrete wall contact, fairly low in the assembly. This outflow location rose with time but remained at the pellet-concrete contact, eventually developing into several small, adjacent outflow locations that can be seen as high water content locations in Figure 6-21. Resistance to inflow was variable but by the end of the test the resistance was essentially nil, with no real resistance being recorded. The movement of water into and through the test is shown schematically in Figure 6-22. Details of the evolution of this test are provided in Appendix A and the results are discussed in Chapter 7.

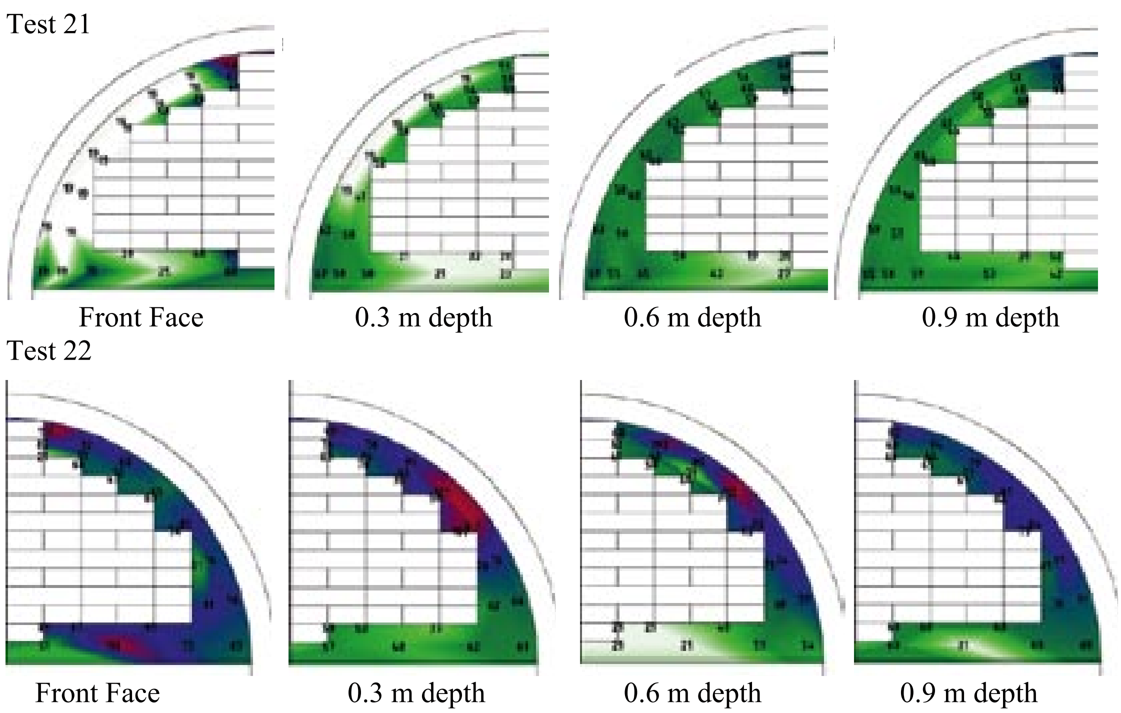


Figure 6-21. *Water distribution at end of test: Tests 19 and 20.*

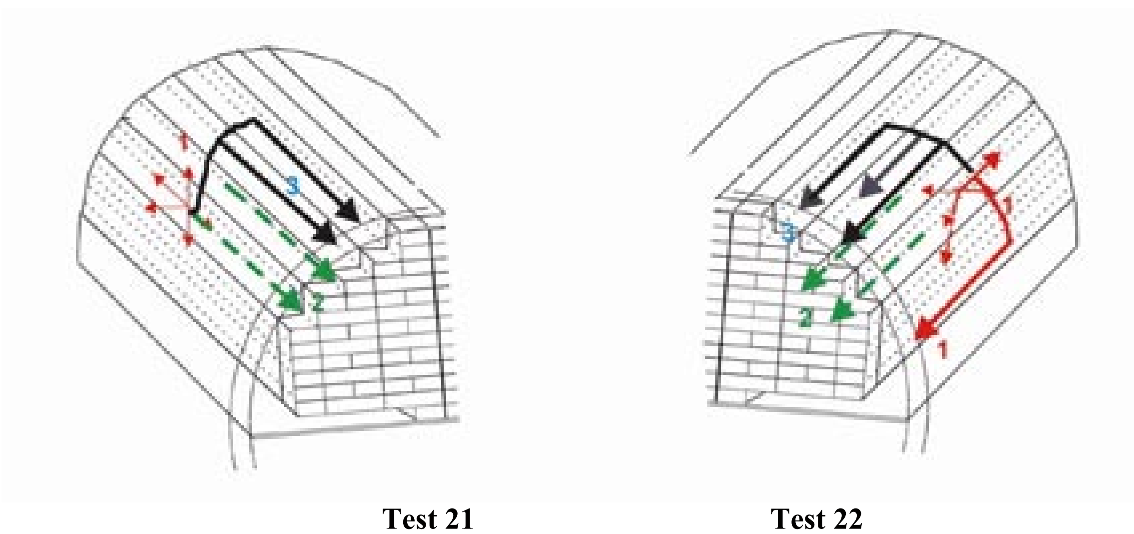


Figure 6-22. *Schematic showing estimated water movement in Tests 21 and 22. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

6.2.11 Tests 23 and 24: 0.1 and 0.5 l/min supplied to floor of chamber

Test 23 had 0.1 l/min supplied to granulate Minelco bentonite materials installed below the block assembly and operated for 24 hours. Water first exited the assembly after 2 hours of operation, via the pellet-floor contact. This outflow was restricted by the swelling of the bentonite pellets and by approximately 7 hours into the test the resistance to flow along this pathway was sufficiently high to force the water to move upwards through the assembly, via the vertical joints between clay blocks. Water then began exiting the system via a pathway developed near the crown of the assembly. The very localized flow path for water along the crown of the assembly can be seen in the water content measurements provided in Figure 6-23 and the flow-path schematic provided in Figure 6-24. More detail on the water uptake and distribution in Test 23 can be found in Appendix A. The resistance to water inflow varied as much as 40 kPa with many sudden increases and decreases. Ultimately at the end of the 24-hour test resistance to flow was averaging 60 kPa. This is approximately the same value as was observed for the other tests installed and run at 0.1 l/min inflow. Appendix A presents the details of water movement into and through the system and the importance of the observations made in this test are provided in Chapter 7.

Test 24 had 0.5 l/min supplied to it for a period of 24 hours although for approximately 17 hours of its operation water flow was not in the manner intended, an unsealed port in the concrete tube 0.6 m from the front face of the assembly became the primary exit location for water. Water began exiting the downstream end of this test after only 3 minutes moving directly from its entry point to the front of the test. Following initial arrival of outflow at the downstream face, seepage was very limited and began to shift toward the centre of the cell. Four hours into the test, water began to exit from between the clay blocks at the upper right side of the assembly. Between 5 and 7 hours into the test, the outflow was primarily from the outside lower corner and the pellets could be seen to be gradually wetting up along the outer perimeter of the system.

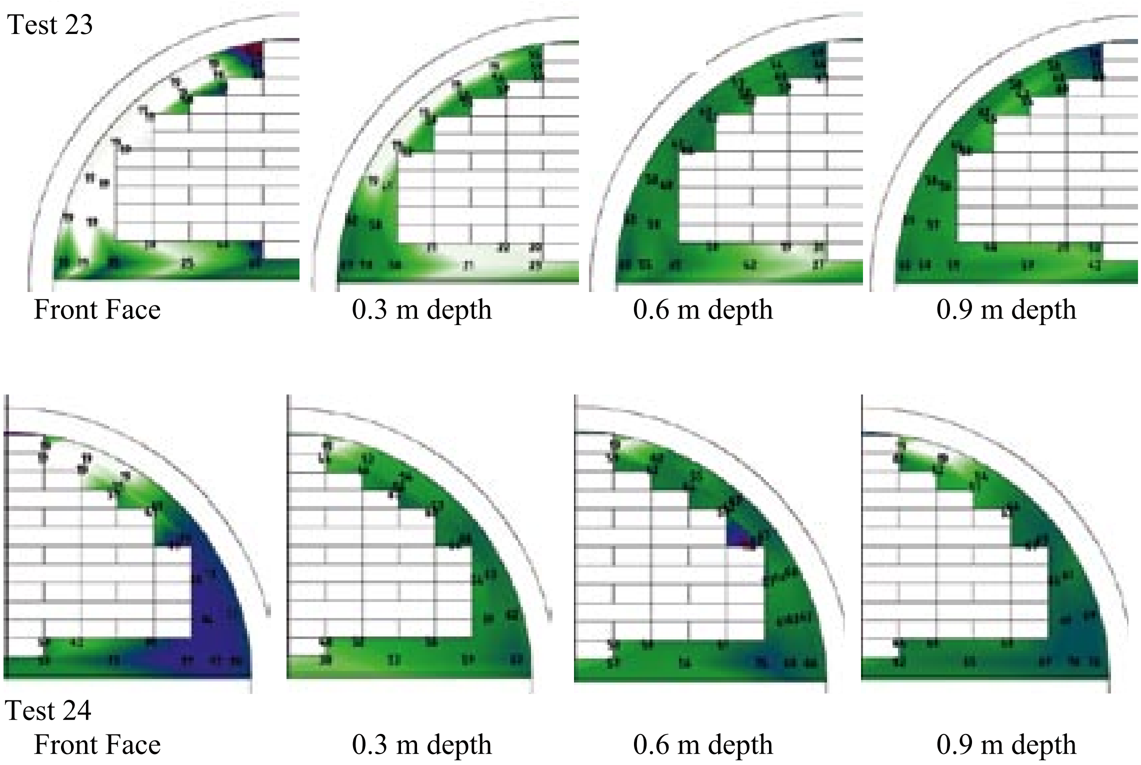


Figure 6-23. *Water distribution at end of test: Tests 23 and 24.*

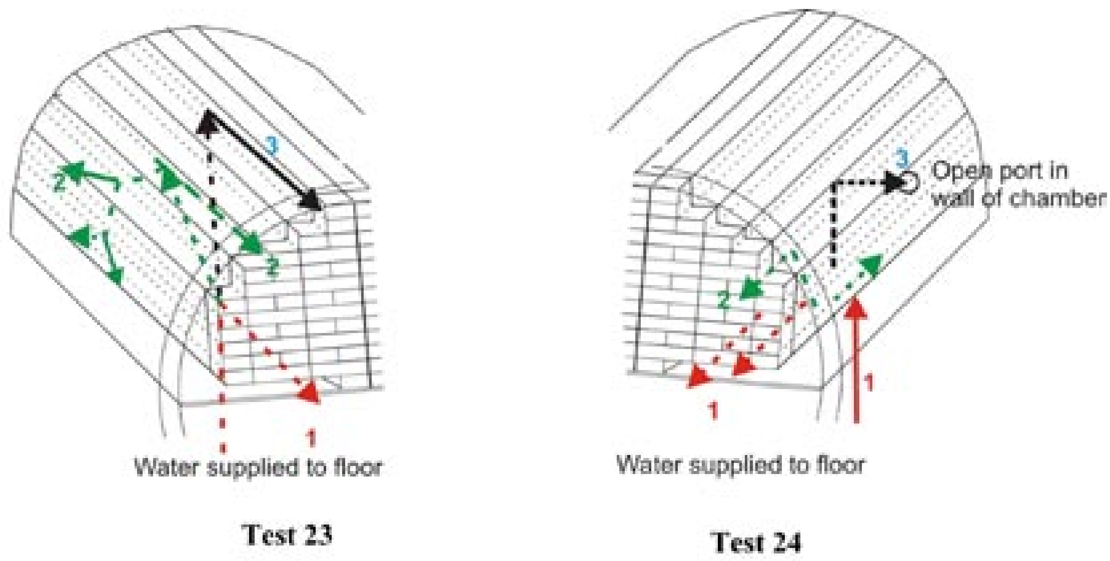


Figure 6-24. *Schematic showing estimated water in Tests 23 and 24. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

At about 7.5 hours into test operation water had moved to the mid-height of the assembly and found an open port in the chamber wall. This rapidly became the preferential flow path within the test and dominated further evolution of the system, its location can be seen in Figure 6-23 and the movement of water is shown schematically in Figure 6-24. This flowpath development also showed up in the inflow resistance values monitored in the course of testing. The somewhat complex development of the test is described in detail in Appendix A and summarized in Chapter 7.

6.2.12 Tests 27 and 28: 0.25 l/min supplied at floor and test mid-height respectively

Test 27 examined inflow of water to a volume of Minelco granulated bentonite. This assembly had Minelco bentonite installed on the floor with Cebogel pellet materials in the remaining annular space. Water was supplied at floor level 0.6 m from the front face of the assembly for a period of 48 hours. Water began exiting the face after 2 hours and 3 minutes of operation along the pellet-floor interface at the centre-left of the cell. This can be seen in Figure 6-25 and Figure 6-26 and is described in detail in Appendix A. Flow rapidly evolved to a single region of outflow close to the original location with considerable material erosion and pulsating flow as water damned and broke free near the front face of the cell. All flow was moving through a single channel along the crushed bentonite-block interface region below the block assembly. By the time that 5 hours of testing had elapsed the outflow rate from this test averaged 0.245 l min for a system having a nominal inflow rate of 0.250 l/min. This flow rate persisted for the remainder of the test and the flow path through the pellet materials. The water distribution at the end of testing can be seen in Figure 6-25 and shows a system that has undergone very limited wetting in the course of its operation. Resistance to water inflow was monitored for the entire test duration and the data also shows a system that very rapidly established a preferential flow path, shown schematically in Figure 6-26. Details of the test, its operation and observations made are provided in Appendix A.

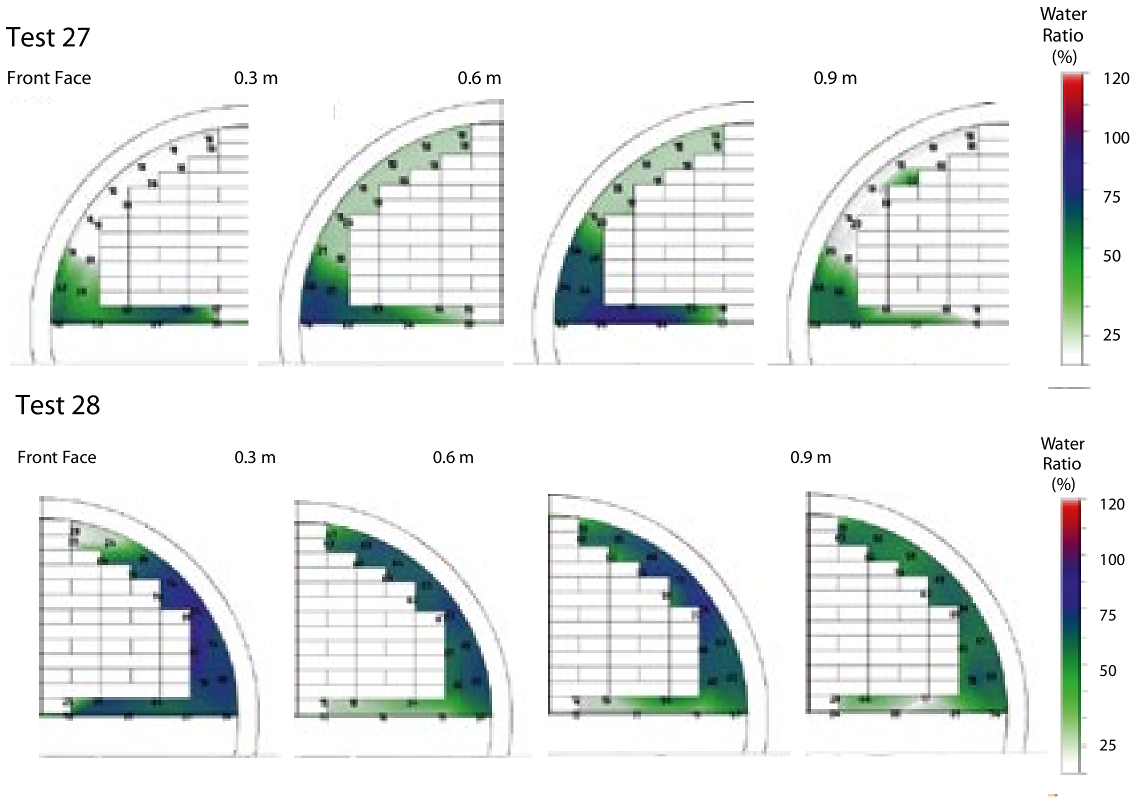


Figure 6-25. *Water distribution at end of test: Tests 27 and 28.*

Test 28 operated at an inflow rate of 0.25 l/min for 48 hours. Like Test 27 it was constructed using granular Minelco bentonite for the flooring material and Cebogel pellets filled the space between the blocks and the concrete tube but in this case water was supplied at the usual mid-height location on the cell wall. Water began exiting the face after 5 hours via the pellet-block horizontal interface at the outside of the block assembly. Flow gradually evolved from wetting at the pellet-block interface region to a single point of outflow close at the concrete-pellet interface at approximately the same elevation as the water injection port. Essentially all flow was moving through this single channel after 24 hours of test operation and it remained unchanging for the remaining 24 hours of test operation. At 24 hours the outflow rate from this test was 0.235–0.245 l/min, ~95% of inflow rate, meaning that there was very limited ongoing water uptake after 24 hours of operation. The pellet and granule materials underwent considerable water uptake by the end of testing, as can be seen by the water content measurements presented in Figure 6-25, but given the limited water uptake after 24 hours this likely occurred in the first day of test operation. Resistance to water inflow was monitored for the entire test duration and is discussed in detail in Appendix A and Chapter 7. These data indicate that the system developed a stable flow path early in its operation (24 hours), through which essentially all the water entering the system moved.

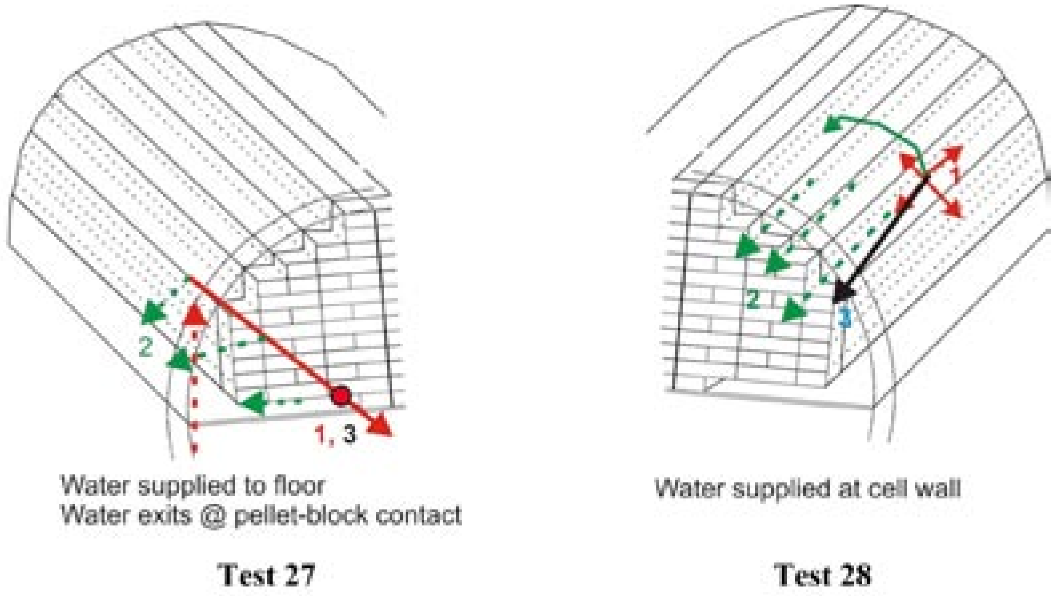


Figure 6-26. Schematic showing estimated water movement in Tests 27 and 28. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.

6.2.13 Test 29: 0.26 l/min supplied only to right-hand side at mid-height of chamber

Test 29 was intended both to study water movement through a block-pellet assembly but also to examine the way in which the two sides of a tunnel might interact if one side saw inflow and the other did not. Tests done previously in this study showed strong evidence of a hydraulic disconnect, at least in the short-term between the two sides of the backfilled volume but this had not been directly studied. Water was therefore supplied to one side of an assembly for a period of 48 hours and outflow monitored. At the end of testing the system was dismantled and carefully examined for evidence of water movement from one side of the system to the other.

Water exited the test after only 70 minutes, but it took several more hours before water outflow began to stabilize in both rate and location. Water initially exited at the lower right corner of the test chamber where the floor, pellets and concrete wall intersected but rapidly shifted to the horizontal block-pellet interfaces, stepwise exiting higher from the test assembly as time progressed. Within 24 hours flow had shifted to a single point at the concrete-pellet interface at an elevation close to that of the inflow port located approximately 0.6 m into the test assembly. Outflow from this interface location was steady, clear (little eroded material) and did not change location for the remainder of the test. The movement of water in the course of testing is shown schematically in Figure 6-28. Figure 6-27 shows that location as a very wet site. Water outflow from the test was monitored and was measured to be 0.260 l/min after 24 hours of operation for a system having an inflow rate of 0.263 l/min and remained in this range until test termination at 48 hours. This indicates essentially no ongoing water uptake by the system once the preferential flow path develops. Figure 6-27 shows a system that had undergone extensive water uptake by the pellet-fill but there was no transfer of water from one side of the test to the other in the time available. Given the extensive wetting that was occurring at the crown it is likely that water transfer from the right-side to the left-side of the crown would likely occur if more time had elapsed.

A detailed presentation of the test's evolution is provided in Appendix A and the key results included in Chapter 7.

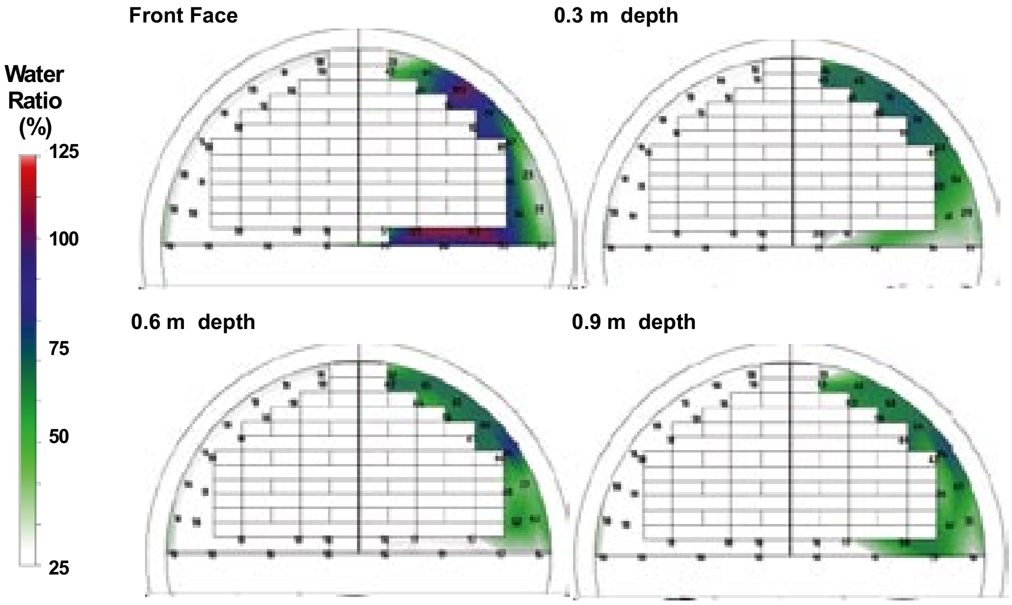
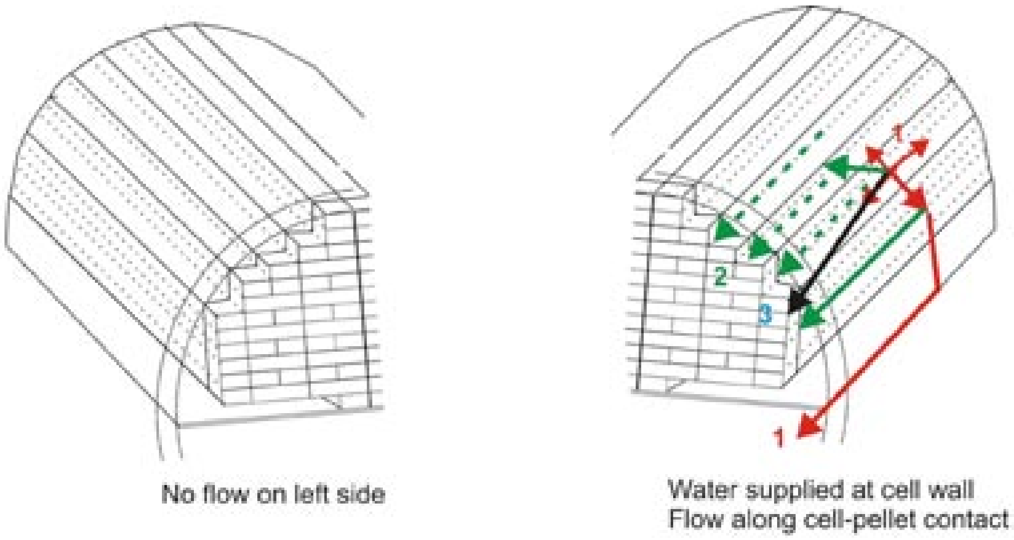


Figure 6-27. *Water distribution in Test 29 at time of dismantling.*



Test 29

Figure 6-28. *Schematic showing estimated water movement in Test 29. Flow Sequence 1 = initial inflow, 2 = secondary flow direction, 3 = flow at end-of-test.*

Table 6-1. Installed Characteristics and Imposed Hydraulic Conditions in Tube Tests.

Test #	Total Volume (l)	Volume of Blocks (l)	Volume of Pellets (l)	Bulk Density of Pellets (kg/m³)	Dry Density of Pellets (kg/m³)	Water Inflow Rate Applied (l/min)	Inflow Distance From Front Face (m)	Testing Time (h)	Time to Outflow (h)	Mode of Outflow at End-of-Test
3	942.3	580.5	361.8	1,340	1,130	0.1	0.6	46.5	2–16	–Horizontal pellet-block contacts @ assembly mid-height
4						0.1			2–16	–“ “ also vertical pellet-block contact close to assembly base
5	942.3	600.8	339.9	1,400	1,180	1.0	0.6	5	0.13	– Horizontal pellet-block contacts
6						0.25			2	– Horizontal pellet-block interface at inflow elevation
7	942.3	600.8	341.5	1,370	1,150	0.01	0.6	118	NM	– No outflow
8						0.03			NM	– Horizontal pellet-block contacts
9	942.3	600.8	341.5	1,350	1,140	0.1	0.6	24	3–20	– Horizontal pellet-block contacts
10						0.25		5.5	2	– Horizontal pellet-block contacts
11	942.3	594	312.4	1,180	990	0.1	0.6	24	3–13	– Concrete-pellet contact
12						0.25		5.5	1.5	– Concrete-pellet at floor and horizontal pellet-block contacts
13						0.5	0.6	5	0.75	– Concrete-pellet at floor and horizontal pellet-block contacts
	942.3	621	312.4	1,260	1,060					
14						0.25		5	5	– Horizontal pellet-block contacts
15						0.1	0.6	24	6	– Concrete-pellet at floor and horizontal pellet-block contacts
	942.3	621	321.3	1,270	1,070					
16						0.25		24	6.3	– Block joints near top of chamber
17						0.1	0.6	48	2.8	– Horizontal pellet-block contacts and block joints
	942.3	621	312.4	1,330	1,090					– Block joints near top of chamber
18						0.25		48		
									1.2	

Test #	**Total Volume (l)**	**Volume of Blocks (l)**	**Volume of Pellets (l)**	**Bulk Density of Pellets (kg/m³)**	**Dry Density of Pellets (kg/m³)**	**Water Inflow Rate Applied (l/min)**	**Inflow Dis-tance From Front Face (m)**	**Testing Time (h)**	**Time to Outflow (h)**	**Mode of Outflow at End-of-Test**
19						0.1	0.6	100	5	– Concrete-pellet contract and horizontal pellet-block contacts
	942.3		312.4	1,310	1,110					
20						0.5		100	2.7	– Block joints near top of chamber
		621								
21			‘			0.1	0.6	48	8–24	– Concrete-pellet contract and horizontal pellet-block contacts
	852	553.5		1,310	1,100					
22			298.5			0.25		48		– Concrete-pellet contact
									4–5	
23	852	553.5	298.5	1,290	1,090	0.1	0.6	24	2	– Block joints near top of chamber
24						0.5			0.05	– Piping feature through blocks
						floor				
25–26	**Tests**	**Were**	**Not**	**Done**						
27	904.4	553.5	352.9	1,180	990	0.25, 0.25	0.6	48	3	– Pellet-block contact on floor
28									7	– Horizontal pellet-block contacts
29	942.4	621	312.4	1,380	1,160	0.25	0.6	48	1.3	– Concrete-pellet contact

Table 6-2. Installed Characteristics and Hydraulic Conditions in Tube Tests.

Test #	Dry Density of Pellets (kg/m³)	Water Inflow Rate Applied (l/min)	Inflow Distance From Front Face (m)	Testing Time (h)	Time to Outflow (h)	Maximum Inflow Resist-ance (kPa)	End-of-Test Inflow Resistance (kPa)	Proportion of inflow exiting at end of Test (%)
3	1,130	0.1	0.6	46.5	2–16	62	62	70
4		0.1			2–16	48	25	
5	1,180	1.0	0.6	5	0.13	45	30	52*
6		0.25			2	22	22	12*
7	1,150	0.01	0.6	118	NM	65	65	0*
8		0.03			NM	80	65	~0*
9	1,140	0.1	0.6	24	3–20	20	18	~0*
10		0.25		5.5	2	10	10	28*
11	990	0.1	0.6	24	3–13	42	42	84
12		0.25		5.5	1.5	22	22	NM
13	1,060	0.5	0.6	5	0.75	22	22	NM
14		0.25			5	23	23	NM
15	1,070	0.1	0.6	24	6	64	64	>4*
16		0.25			6.3	85	75	97
17	1,090	0.1	0.6	48	2.8	80	80	>78
18		0.25			1.2	98	50	>76
19	1,110	0.1	0.6	100	5	98	80	>90
20	1,110	0.5	0.6	100	2.7	55	45	~100
21	1,100	0.1	0.6	48	8–24	50	50	>56
22		0.25			4–5	65	10	>74
23	1,090	0.1	0.6	24	2	90	60	>13*
24		0.5			0.05	72	62	NM(>90)
		floor						
27	990	0.25 floor	0.6	48	3	68	15	98
28		0.25			7	70	70	>94
29	1,160	0.25	0.6	48	1.3	50	45	>98

* Note these tests were not operated long enough for outflow to develop fully or stabilize, hence very low outflow proportions.

7 Assessment of behavioural trends and linkages

The preceding sections have examined the behaviour of the 27 tests conducted as part of this study on a case-by-case basis detailing the behaviour of each test. From these detailed data it is possible to develop some generic behaviour expectations for systems consisting of mixed backfill block and granular/pellet filled systems that approximate the situations that may be encountered in a tunnel. The compilation of the flow resistance, inflow and outflow behaviour and other basic responses of composite pellet-block backfilled systems are discussed in the following sections. As there are likely to be concerns related to time between backfill placement and water outflow, inflow rate and time to exit from the backfill as well as the potential for erosive activity these topics are discussed separately below. There is of course overlap between these topics since there is a linkage between flow rate and time to water exit as well as time, flow rate and mass of material eroded. There will therefore be some degree of repetition in the discussions contained in this section but for the purposes of examining each of the overlapping effects of the parameters of time, flow rate and erosion this is unavoidable.

7.1 Influence of time on observed behaviour

7.1.1 Behaviour over short time period (<6 hrs)

Of the 27 tests done as part of this study, six were operated for less than 6 hours. These very short duration tests were amongst the first tests done as part of this study and provided some initial guidelines for anticipating the evolution of the longer-term tests, as well as recording the initial water movement patterns within the backfilled volume. The short duration of these tests make them inappropriate for the study of relatively low water inflow rate systems and so only systems having inflow rates of 0.25, 0.5 and 1.0 l/min were operated for such short time periods.

These tests provided limited information on the longer-term behaviour of the backfill systems as stable flow was not established in the available timeframe. They do however provide a measure of what might be encountered during ongoing backfilling operations where a region of high water inflow is present. Issues identified related to outflow and erosion in such short time periods will be important in determining what conditions are problematic in routine backfilling activities in a repository. Where outflow was observed in these short-term tests, initial outflow typically occurred first at or near the bottom outside corner of system. Where outflow was established there was subsequent wetting and fluid flow out of system along horizontal block – pellet interfaces with the elevation of the outflow point increasing with time. Associated with early stage outflow in systems containing Cebogel pellets was a flushing of bentonite fines from the pellet-filled region but this was not usually more than trace amounts and did not affect either flow behaviour or backfill stability.

In none of the tests done in this series was there a serious issue related to the physical stability of the block-pellet assemblies, however water exiting the tests would need to be dealt with in an actual tunnel situation and could prove problematic for ongoing backfilling operations.

7.1.2 Tests operated 24–48 hours

The majority of the tests undertaken as part of this study operated for 24 to 48 hours, a time that would be representative of anticipated interruptions in backfilling operations (e.g. weekends, holidays, equipment down-time or other causes). The stability and water uptake/outflow behaviour of the backfill over this time frame is of considerable interest to operational planning as this type of interruption in operations can be anticipated in an operating repository. The materials examined in this study show an ability to remain physically stable for this time period provided that some support is provided at the downstream end (rigid steel mesh), but can undergo considerable water outflow from the face of the backfilled volume and also experience considerable erosion as the result of this outflow.

For systems where inflow rate to the region immediately behind the working face (in this study 0.6 m) water can routinely work its way through the backfill in a matter of a few hours if the inflow rate is 0.1 l/min (6 l/h) or more. Time to water exit from the face of the backfilled volume was observed to be directly proportional to the inflow rate as can be seen in Figure 7-1. The exiting water can be observed in a range of locations at the face of the backfilled volume but for tests operated more than 48 hours outflow locations tended to evolve towards discrete flow paths at the "rock" pellet interface, provided that an internal piping feature did not develop. Water being supplied 0.6 m from the working face can induce piping features within the block-filled portion of the backfill and even at 0.1 l/min (6 l/hr) for a period as little as 48 hours considerable erosion and disruption to the backfill can occur (see Appendix A for details).

In general, for periods of 24–48 hours after initiation of limited water inflow (<6 l/h), the downstream face of the backfilled volume (0.6 m distant from water source), the backfill can be assumed to be physically stable. If interruptions in excess of this duration or in regions where higher inflow exist, there should be physical support provided to the backfill in order to minimize the risk for slumping or ongoing erosion of material from the backfill. At inflow rates in excess of 0,25 l/min (15 l/h) in close proximity to the face of the backfilled volume, there is a clear issue related to piping, erosion and likely physical stability of an unsupported backfill if it continues for more than two days. For longer-duration periods of operational pauses there will be a need to provide some form of water control/drainage or else the inflow points in the tunnels will need to treated in order to ensure that they do not provide sufficient water to be problematic during backfilling operations. There are also other practical means to control the situation. E.g. the inflow points should be mapped in advance and the operations should be timed so that this kind of section is not backfilled just before weekend or another expected pause in backfilling operations.

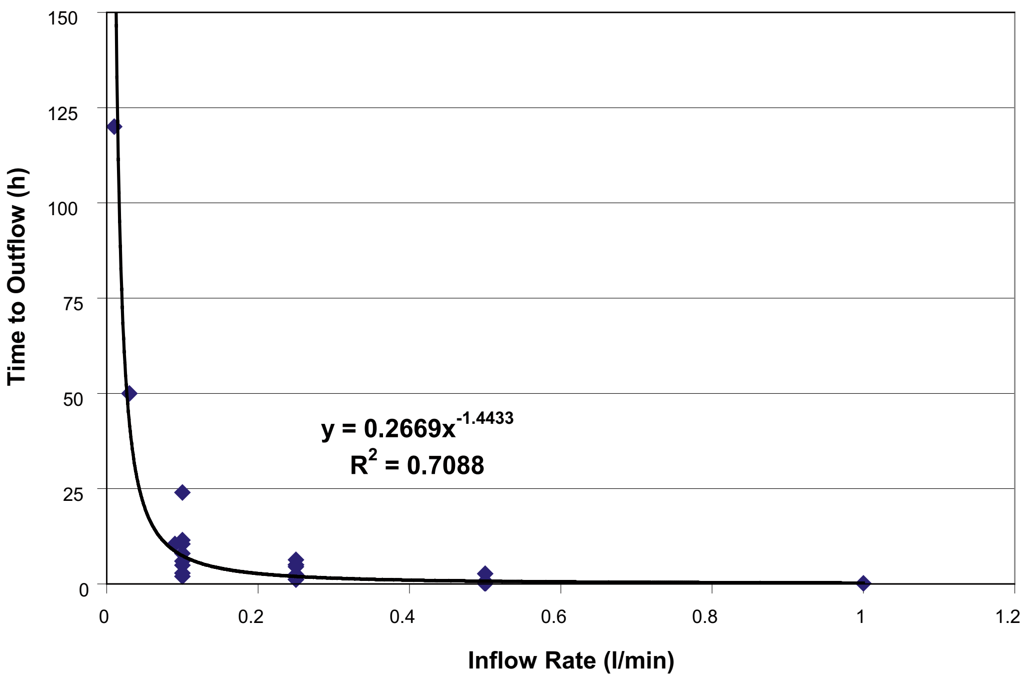


Figure 7-1. *Time to outflow at various inflow rates.*

The exception to the general behaviour pattern summarized above for low flow rates entering the backfill for short – to – intermediate durations (<48h) is if flow is entering from the floor of the tunnel. In this situation rapid water movement towards the face of the backfilled volume or upwards through the block-filled volume can be anticipated. This can result in considerable erosive action on the backfill and could lead to physical instability of the backfill during a break in placement operation.

7.1.3 Long duration tests (48–120 h)

A number of tests were operated for extended durations (48–120 h), which represent times where a substantial interruption to backfilling operations has occurred. Tests operated for this timescale ranged in water input rates from 0.01 to 0.5 l/min. At inflow rates in the order of 0.1 to 0.25 l/min, initial flow occurred along the block-pellet interface as the system underwent initial wetting and before the pellets had time to swell and begin to restrict water movement. With time flow within the assembly generally ceased and relatively stable flow paths typically developed along the "rock" – pellet interface. Water then moved along this interface with little resistance and was typically not particularly erosive. However in a number of cases water found a pathway to and through the Friedland clay block assembly, generating highly erosive flow paths. Over an extended period, this would result in compromising of the backfill performance and physical stability. The effect of this ongoing erosion can be seen in Figure 7-2 where the test operated at 0.5 l/min over a period of approximately 100 h experienced a progressive lessening of its ability to resist inflow. This behaviour may also have been developing at a flow rate of 0.25 l/min with the sudden drop in inflow resistance after approximately 2 days of inflow (Figure 7-2). These erosive processes and resultant features are summarized in Section 7.3 where erosive processes and behaviour are summarized.

7.1.4 Summary of role of time on backfill behaviour

Time is clearly an important factor in determining the condition and behaviour of a backfilled volume that has been left unrestrained and where backfilling operations have ceased (either for operational reasons or in order to prepare for installation of drift or room plug). Where water is entering the backfilled region close to the end of the volume backfilled (0.6 m in this study), there is only a limited timespan available before water begins exiting the face of the backfilled volume. With low inflow rate the time available is generally longer than where high inflows are present (Figure 7-1). However, this is not necessarily a directly proportional relationship, as can be seen in the range of outflow initiation times in Figure 7-1 for the same inflow rate (e.g. 0.1 l/min). Time before water exits the system will depend more on the relatively random water uptake pattern at the contact between the pellets and the rock. The presence of a considerable hydraulic gradient from the inflow location to the open excavations will also tend to drive a process whereby the water tries to find a pathway of limited resistance through the backfilled system.

7.2 Role of inflow rate on backfill behaviour

7.2.1 Behaviour at low inflow rate (<0.05 l/min)

The stability of assemblies exposed to very low rates of water influx was not anticipated to be problematic and the two long-duration (120 h) tests (Tests 7 and 8), conducted at 0.01 and 0.03 l/min confirmed this prediction. These tests typically showed patterns of incomplete wetting of the pellet fill, limited wetting in crown and base regions, essentially no outflow from the tests, very little wetting of blocks. Where outflow was observed, it typically occurred along the pellet-block horizontal contacts. Figure 6-7 shows the pattern of water distribution after 120 hours of water inflow and illustrates how limited the volume of water supplied was and the uniformity of the wetting that occurred. The inflow resistance for such low water input systems

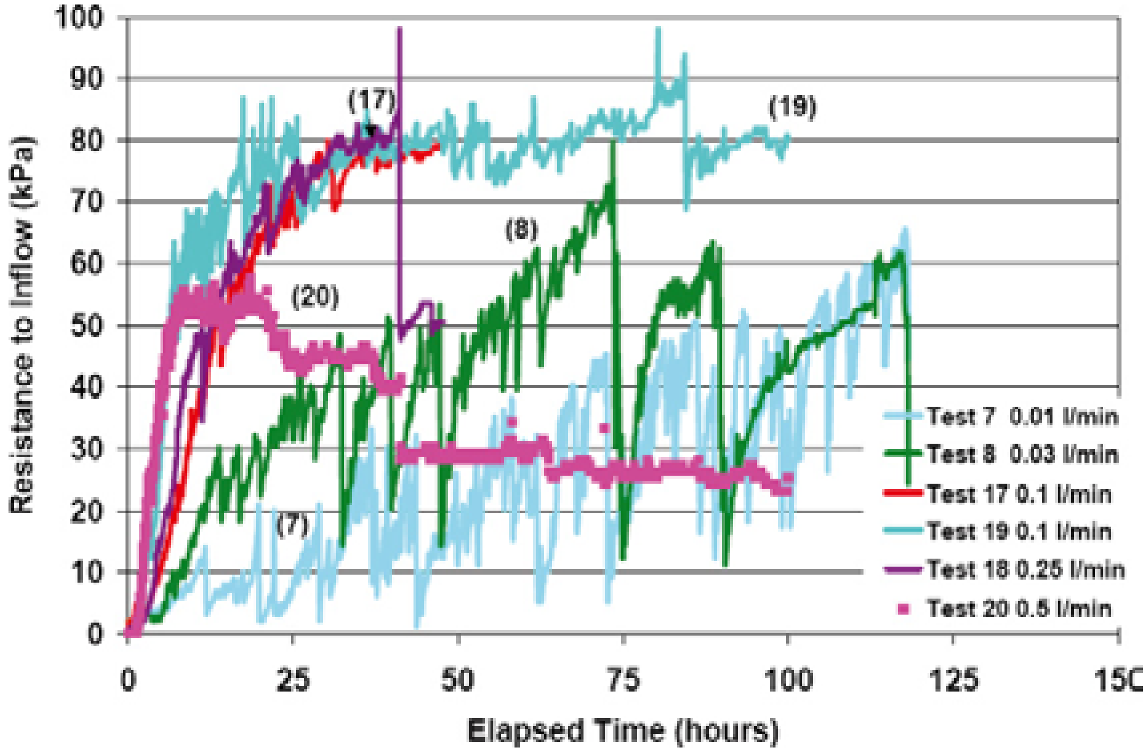


Figure 7-2. Inflow resistance in longer-duration tests.

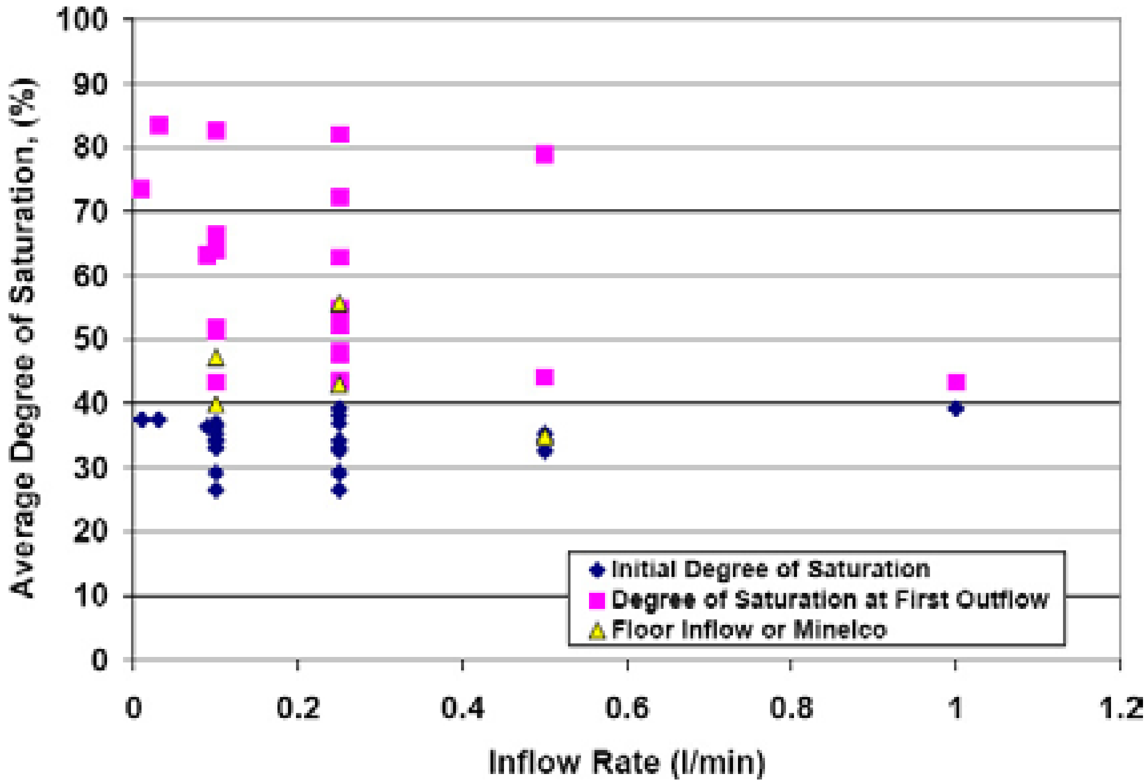


Figure 7-3. Inflow rate and degree of pellet saturation before outflow.

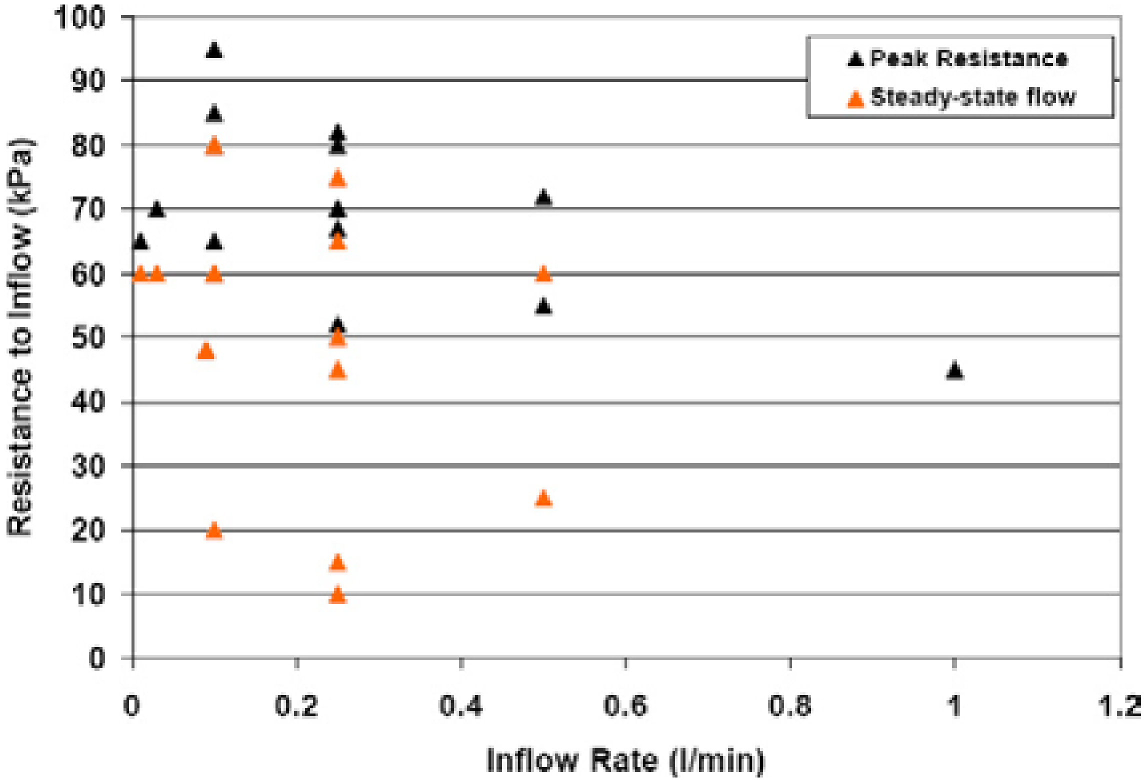


Figure 7-4. *Change in resistance to inflow.*

showed considerable variability and this is interpreted to be the result of the wetting-plugging-pushing through to new dry region, cycle that was occurring at a very small scale in these systems. Details of these two tests can be found in Appendix A.

The magnitude of resistance to water inflow in such tests showed a pattern not dissimilar to systems having higher inflow rates. There was evidence of the development of new flow paths with time (sudden changes in flow resistance) as well as an overall trend towards increasing resistance to inflow with time. Based on the low magnitude of the inflow resistance, it is anticipated that once these systems achieved a sufficiently high degree of water saturation, that inflowing water would develop some form of preferential flow path. It would likely develop along an interface (concrete-pellet) and a relatively constant resistance to inflow would be evident. In terms of backfilling operational considerations, such low inflow rates (< 0.03 l/min, 2 l/h) do not appear to cause any issues related to water outflow or system stability over a period of at least 4 to 5 days, if the backfilling operations for some reason ceased. This can be interpreted to mean that for normal, anticipating backfilling operations where several meters (est. 6 m/d) of backfilling occurred each day, that the backfill will remain stable, provided some support is provided at the downstream face.

7.2.2 Inflow rate of 0.1 l/min (6 l/h)

A total of 9 tests were done at a fixed rate of 0.1 l/min (6 l/h) water inflow for times ranging from 24 to 100 hours and representative tests are presented in Figure 7-5. The behaviour of these tests was strongly influenced by the location where water entered the cell, indicating that in a field situation, this will be an important consideration. Where water was entering from a floor location there was a shorter time to first exit from the system and a lower degree of overall system saturation at the time of test termination. There was considerable variation in the manner in which these systems evolved, largely associated with where and when preferential flow paths developed and how long the test operated.

The general observations associated with water uptake and movement made in the course of testing systems at an inflow rate of 0.1 l/min were that:

1. Wetting generally occurs along sides of test cell (pellet-filled region) first.
2. Base of test cell is last area to wet (where inflow occurs above floor level).
3. Generally limited water entry occurs along block joints.
4. Outflow generally evolves to include the horizontal contacts between pellets and clay blocks.
5. Outflow from system (0.6 m distance from inlet) will occur in 2.8–15 h.
6. Piping can occur in and through the clay blocks (observed in 1 test of 8).
7. Piping can be highly erosive in nature.

7.2.3 Water inflow rate of 0.25 l/min (15 l/h)

A total of ten tests were undertaken where water inflow was set at 0.25 l/min (15 l/h), for durations of 4.5 to 48 hours. Of these, 7 were constructed using a single type of pellet/granule fill and the remaining 3 were systems constructed using Minelco bentonite as a base material below the blocks and Cebogel in the remaining volume between the block assemblies and the wall of the concrete tube.

Those tests done using a single filler material (Cebogel), between the blocks and the concrete showed a general pattern of behaviour that can be summarized as follows:

1. Rapid wetting of outer perimeter of pellet fill.
2. Subsequent wetting of pellets near crown.
3. Gradual wetting of pellet below block assembly.
4. Gradual wetting of blocks.
5. Outflow from system occurs at 1–6 h.
6. Flow along block-pellet contacts is able to induce erosive flow channelling in some of the tests undertaken. Initiation of substantial erosive activity is indicated by sudden sustained decrease in flow resistance at 36–40 h in Figure 7-5.
7. Ultimately, unless internal erosive behaviour develops, preferential flow path(s) will develop at the concrete (rock) – pellet contact.

7.2.4 Water inflow rates of 0.5 and 1.0 l/min

There were four tests done at inflow rates of 0.5 and 1.0 l/min (30, 60 l/h) but only one test operated for more than 24 hours (at 0.5 l/min). The resistance to inflow developed by these tests is presented in Figure 7-5 and shows an ongoing reduction in resistance to water inflow, as the result of development of erosive flow paths through the system. The general evolution of the systems is as follows:

1. Rapid wetting of pellets, including materials underlying blocks.
2. Nearly complete wetting within pellet-filled volume by 5 hours into test.
3. Substantial water movement into joints between clay blocks.
4. A tendency for water to flow along phreatic surface of pellets as saturation progresses and pellet-block interfaces as saturation is approached.
5. Once saturation of pellet-filled volume is well advanced flow tends to channel to a limited number of flow paths at the pellet-concrete interface.
6. With extensive pellet wetting and extension of wetting into clay blocks there is a risk for the development of piping features and erosive water flow along the pipes that can pass through the clay-block assembly or along pellet-block interfaces.

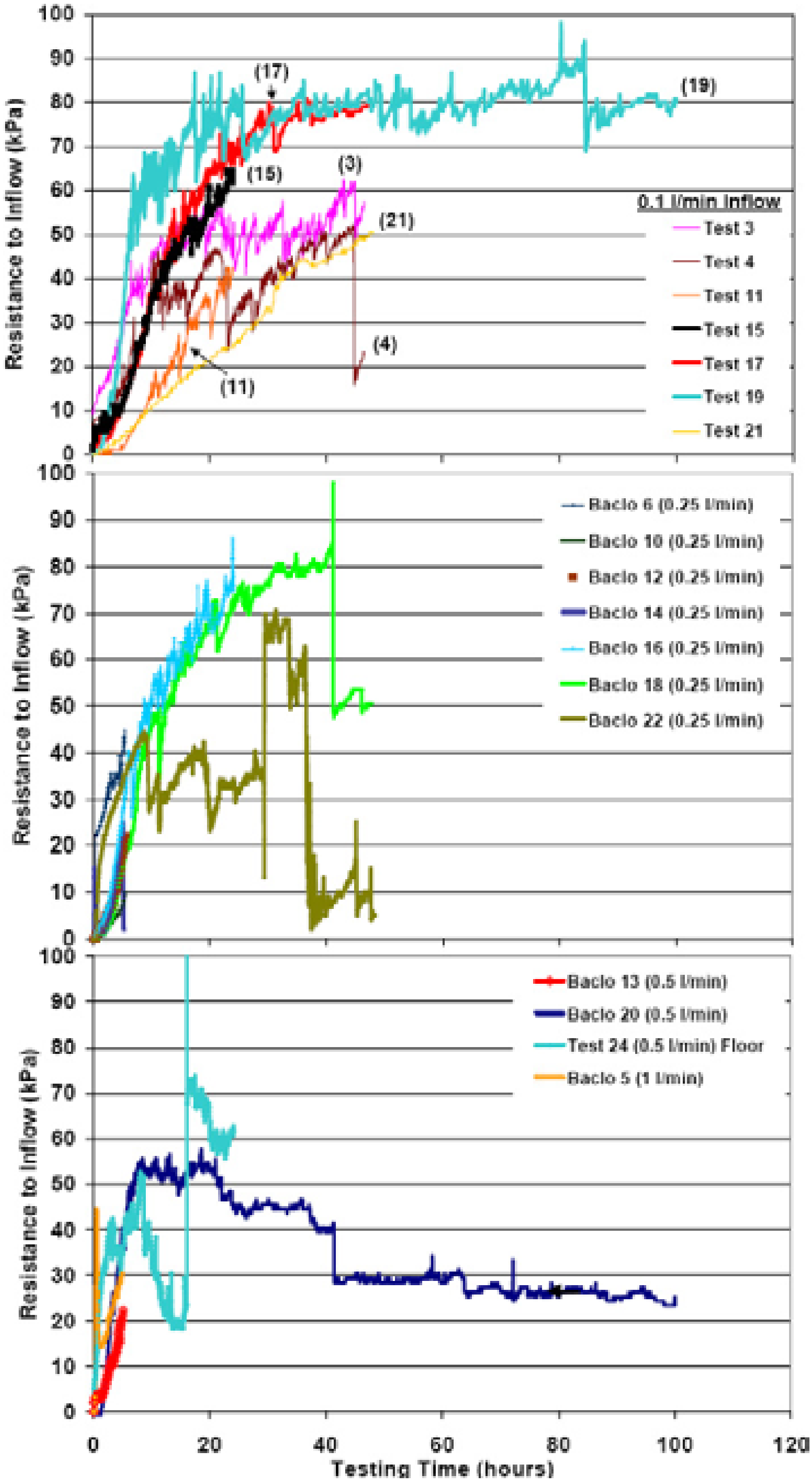


Figure 7-5. *Development of inflow resistance in backfill block – pellet systems.*

The test operated at 0.5 l/min for approximately four days developed very distinct erosive features and had a considerable proportion of its mass moved out of the backfilled region. This process is described in more detail in Section 7.3.

7.3 Influence of pellet type on observed behaviour

This testing series included several tests done where granular bentonite rather than processed and pelletized bentonite was as either a flooring material below the clay blocks (Tests 27, 28, 29) or else totally replaced the pelletized material (Test 21, 22). These tests experienced different water uptake and inflow resistance behaviour than systems constructed using pelletized materials only.

The granulated bentonite material examined (Minelco) was described previously in Section 4 and it proved to be more prone to development of erosive flow paths than the pelletized bentonite (Cebogel) at inflow rates of 0.25 l/min. At inflow rate of 0.1 l/min the granular Minelco material actually exhibited a much lower erosion rate than similar tests constructed using pellet materials. This can be attributed to the rougher surface texture and greater quantity of fines present in this granular material and hence a greater ability to absorb the inflowing water in the early stages of testing. The result is a more uniform wetting pattern adjacent to the inflow point and as a result a more uniform resistance to subsequent water inflow, encouraging the water to find a flow path other than through the granular bentonite. The easiest location for such flow to occur is at the concrete-granular contact where stable flow channel(s) formed and very little subsequent erosion or wetting occurred.

Granular material, when used as a flooring material in conjunction with the pelletized materials (used to fill upper regions), tends to provide a more stable base than pellet-only systems when water is supplied to the upper regions of the assembly. Water entering the system along the walls where pellets are present tends to be prevented from moving freely into the basal regions, as shown in Figure 7-6. As a result, the base of the backfill block-filled region remains dry and so can be expected to maintain its mechanical strength and stability for a longer period. This will increase the likelihood that such a system could remain stable for the period during which backfilling operations were interrupted. In contrast, granular-filled regions experiencing direct water inflow (wall or especially floor) showed a tendency towards limited resistance to erosion and development of narrow regions of saturated clay and preferential flow paths through the assembly as shown in Figure 7-7. These pathways could also be quite erosive in nature, removing considerable material as water moved out of the test. There may be an opportunity to vary the materials used for basal fill in order to improve the short-term mechanical stability of the backfill but this will require knowledge of the local water inflow locations and patterns and will require considerably more evaluation before it can be implemented.

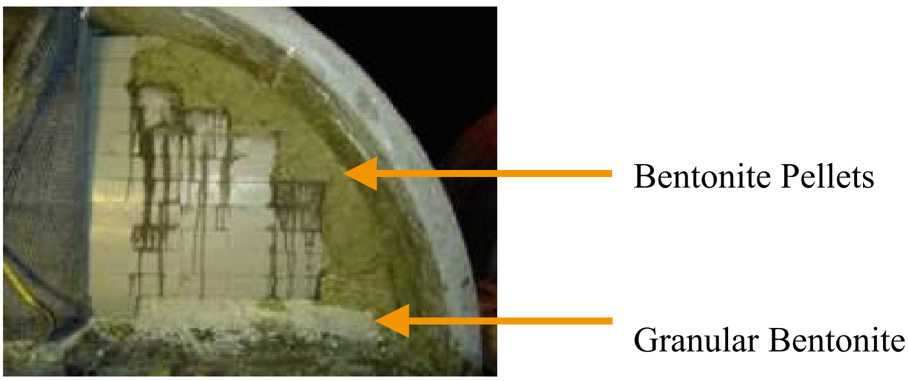


Figure 7-6. *Development of a hydraulic disconnect at the pellet-granular contact (dry, light-coloured granular materials on floor and dark-coloured wet pellets along walls).*

***Figure 7-7.** Narrow, preferential flow path through granular material (Test 27). (Dark semicircle showing where water flow and uptake occurred, some wetting on floor to left of this feature also occurred).*

7.4 Water outflow and erosion

One of the primary concerns related to backfilling and especially situations where backfilling operations have been interrupted for a period of time beyond a few hours is the potential for erosion of the backfill by water entering the tunnel somewhere in the already filled region. Movement of water through the backfill has the potential to develop preferential flow paths, as has been clearly shown in these large-scale tests, as well as laboratory tests done part of the Baclo project /Sandén et al. 2008/.

Previously presented test information has established that there is no requirement for the backfill system, or even the pellet/granular materials to reach saturation before water exits the system. Once flow out of the system has been established there is the question of what proportion of the inflow is exiting the system and how much is being retained by the backfill as it moves towards saturation.

The series of tests described in this report provide measurements of the quantities and rates of backfill material (pellet, granular or block) removal over the period of 2 to 5 days. They also provide indications of the time-dependent erosive behaviour of water that is flowing into, through and out of the tests. Given the manner of flow observed in most of the tests done in this study it is possible to begin to develop estimates of the conditions that are likely to develop in the field. Quantification of erosion rates and quantities in these tests provides a means of developing predictions for the situations likely to be developed in larger (e.g. ½-scale tests planned for 2007/8 at Äspö) simulations and in full-scale field conditions.

Erosion and erosion rates were somewhat difficult to measure in this test series. The measurement of eroded materials was not initially a component of this test series but the opportunity, once recognized, to quantify erosion rate and quantity proved to be a valuable addition to the scope to these tests. Tests that were run for only very short times could only have the eroded material collected as completely as possible and the amount of material lost estimated. Tests run for 48 hours or more were more amenable for conduct of erosion rate and quantity measurement.

There were two approaches taken to determining erosion rate and quantity of eroded material in the longer duration tests (>24 h duration). Shorter-term tests provided limited information on the erosion behaviour of the system as they only ran long enough for the initial outflow to occur, together with early erosion from the system. The loss of material in the first 24–48 hours was typically quite high and was dominated by fines being flushed from the pellet materials or else sediment lost from the Friedland clay through changing flow paths and initial outflow along the vertical downstream face of the block assembly as the tests underwent initial wetting.

As described previously, the tests were equipped with outflow collection systems to capture and measure the water exiting the set-ups. By monitoring the mass of the water collected per unit time the outflow rates were determined and at the same time the outflowing water contained much of the eroded material, which when decanted and added to sediment that remained in the outflow tray provided a mass estimate for the material removed by water flow. In several tests there were regular samples of the water exiting the assembly taken and the sediment load in each of these samples could be used to estimate the rate and quantity of sediment exiting the test. The third means of measuring the rate of material loss by the backfill involved the same water collection system as was used to collect the outflow. However in this case where the collection system overflowed (as it did at night when it was not possible to empty it), the result was deposition of sediment-loaded outflow into the large collection buckets, settlement out of the solids to the bottom of the bucket and overflow of the bucket, allowing the relative clear water to exit the system. The mass of the remaining sediment was recorded using the load cells used to monitor the buckets. As the sediment increased in the bucket, the weight increased but the volume of the water in the bucket remained essentially unchanged. Change in mass can therefore be attributed to eroded materials.

Neither technique is absolutely accurate as there are mechanisms whereby mass can and is lost in the course of testing. In the accumulation of sediment throughout the test there is a component that is too fine to settle out and is lost in the course of testing. This technique only provides a total mass estimate and provides no quantitative measure of changing erosion rates. The measurement of settlement of solids in an overflowing collection system is also prone to the loss of solids that do not settle out sufficiently quickly. Observations made during the testing indicated that this quantity was relatively small however (only slightly cloudy effluent). The overflow technique also does not allow for changing flow rates to be detected and is subject to underestimation of the erosion rate if the sediment does not travel from the face of the test set-up to the collection bucket (accumulates on tray before bucket). It is most valuable therefore to use both sets of data to provide an indication of the outflow rates and the mass of material removed in the course of testing.

7.4.1 Outflow rates and establishment of steady-state outflow

The pattern of inflow quantity, measured outflow quantity and resistance to inflow on several of the tests done at 0.1, 0.25 and 0.5 l/min inflow rates are presented in Figure 7-8. These figures clearly show rapid development of and sustained presence of outflow rates that were essentially identical to the inflow rate. That none of these tests were at or near-saturation (saturation of the pellet macropores) at the time of first water outflow demonstrates that once water outflow paths are established, only a very gradual rate of water uptake by the remainder of the backfilled volume will occur (including the pellet-filled regions). Figure 7-8 also clearly shows that there is little effect of inflow rate (once it exceeds ~0.1 l/min), on the proportion of water that rapidly exits the system. Almost as soon as outflow begins, essentially the entire volume of water entering the system moves rapidly and directly through established preferential flow path(s). It will therefore be necessary to be prepared to deal with whatever volume of water is entering the backfilled system as soon as it finds a pathway through to the working face. This will make minimizing water influx into the volumes to be backfilled of considerable importance in an operating facility. It will also make it important to ensure that ongoing backfilling operations are not interrupted for unacceptably long times.

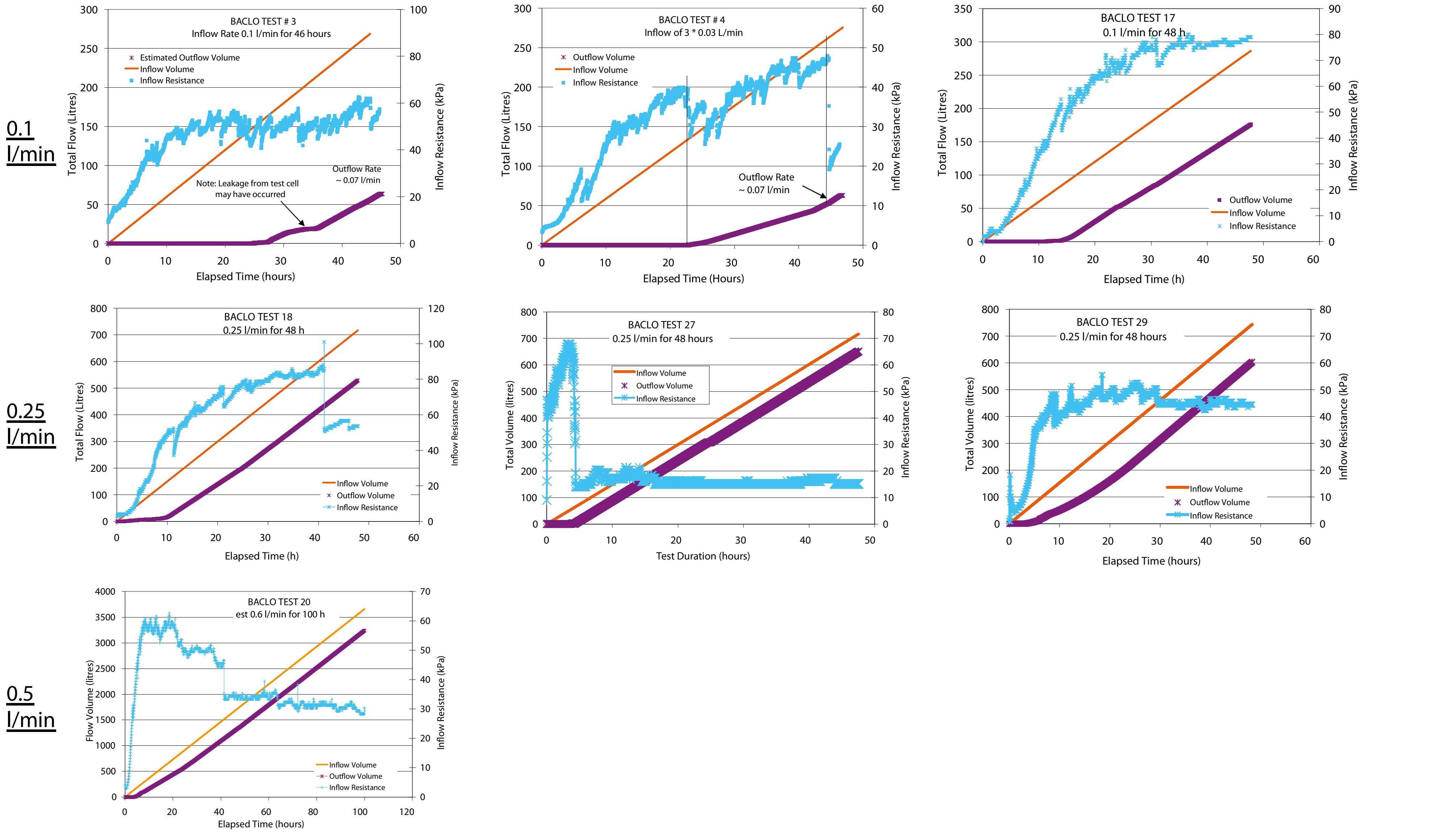


Figure 7-8. *Inflow – outflow patterns and inflow resistance.*

7.4.2 Measurement of erosion rate

Typically, sediment entrained in the water exiting these tests entered a collection system that was equipped to monitor the mass of exiting material (water and sediment) as shown in Figure 3-4. This setup allowed two approaches to be used in estimating the amount of erosion occurring as the result of water flow:

- In the first setup, all of the water was collected either in the buckets or else in larger barrels located below the buckets. As the buckets were emptied and reset, the water in the buckets was decanted into the larger barrels, leaving wet sediment behind. The decanted water in the barrels was decanted again at the end of the test to capture the remaining sediment. This sediment was accumulated for the duration of the test ultimately was dried to determine the total mass of material removed.
- The second method of determining the total erosion also allowed for estimation of the erosion rate. When the collection buckets overflowed (as occurred during the night when emptying of buckets was not possible), the water still first entered the buckets. This set-up allowed the coarser materials in the outflow solution to settle out to the bottom of the bucket and relatively sediment-free water to then flow out of the top of the bucket. Decanting of the buckets and barrels allowed the total mass of sediment to be determined, as occurred in the first method. The overflowing bucket system also allowed estimation of the erosion rate and quantity on a real-time basis. The sediment that settled out into the buckets caused the mass of the collection system to gradually increase but the volume contained by the bucket remained constant. As a result, increasing total mass can be attributed to sediment accumulating in the bottom of the bucket. This type of monitoring could only be done on systems where water outflow was sufficient to cause overflow and where extended periods of overflow occurred. This meant that the shorter-duration tests were not suitable for this type of monitoring and similarly those tests where outflow bypassed the collection system could not be assessed in this manner.

With the inherent uncertainties between the two sediment collection approaches described above, two sets of calculations were done to obtain estimates of the material removed in the course of the tests. Table 7-1 provides a summary of these estimates and although there is some variability in the results, the magnitudes predicted for each test are comparable. In Table 7-2 the inflow and outflow volumes are summarized and the quantity of water taken into the test are estimated. These data provide an indication of the ability of water to bypass the backfill and exit the system directly.

A plot of the total mass of material lost from each test versus flow rate applied is presented in Figure 7-9. Figure 7-9 does not take into account the different test durations (5 h to 118 h) for the various flow rates but there is a general trend towards increasing erosion with increasing flow rate. A more informative way to assess this data is to plot the average erosion rate (grams per litre of outflow water), for entire test duration against the inflow rate as shown in Figure 7-10. In Figure 7-10 the average concentration of eroded sediment per litre of water seems to relatively independent of the flow rate, although at high flow rate (0.5 l/min) there appears to be a higher basic erosion rate than was seen in other tests (no average erosion rate less than 10 g/l were observed).

Beyond the assessment of total erosion and average rates of erosion for the various flow rates and testing times there is clear evidence that long-term average erosion rate decreases with testing time and is apparently less related to flow rate than is the short-term behaviour. Figure 7-11 shows the erosion rates recorded at various times at three different inflow rates. These data indicate that the systems operated at 0.1 and 0.25 l/min water inflow rates did not experience substantial erosion when flow occurred along the pellet-concrete (rock) interface and showed a trend towards stable flow and erosion rates that were less than or equal to approximately 0.1 to 0.2 kg/h (or 10,200 g/h) (~0.02–0.05% of pellet mass per hour). Where inflow rate was 0.5 l/min (30 l/h) there was a very different pattern of erosive behaviour. These high-flow systems showed early, highly erosive behaviour as they developed flow path(s) that could transfer the water with minimal resistance to the downstream face of the backfill. This erosive behaviour persists for

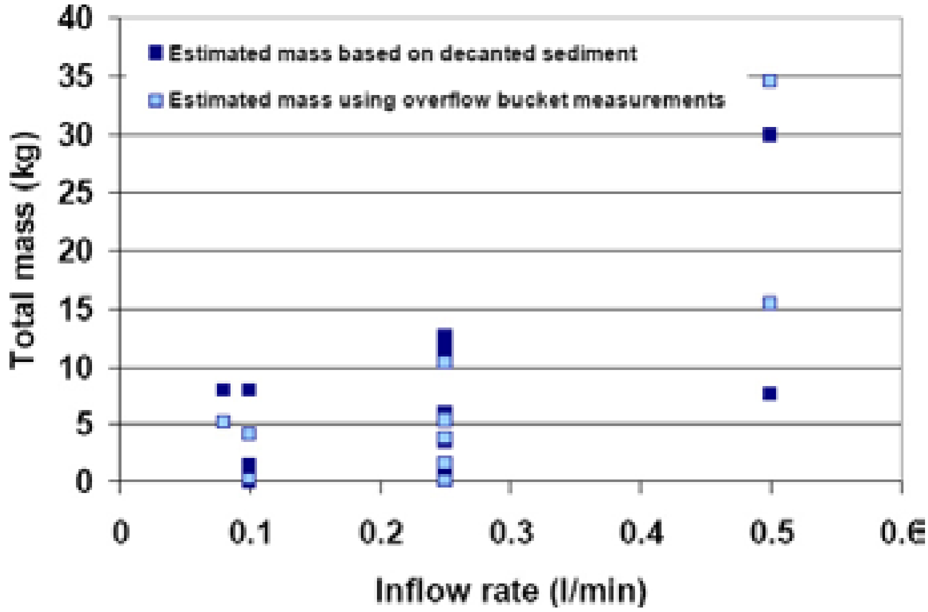


Figure 7-9. *Influence of inflow rate on the total mass of eroded materials.*

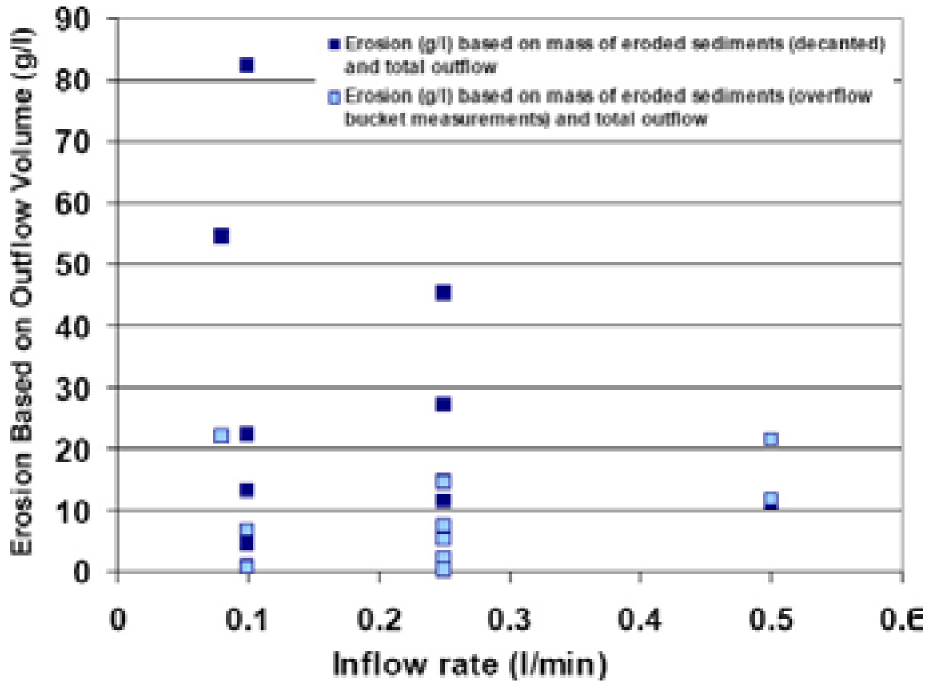


Figure 7-10. *Influence of flow rate on sediment load per litre of water exiting tests.*

Table 7-1. Summary of erosion rate and quantity measurements (M = milos granulates, MC = milos granulates on the floor and cebogel pellets elsewhere) (tests operated >24 h).

Test #	Inflow rate (l/min)	Test Duration (h)	Estimated mass based on decanted sediment (kg)	Estimated Mass using overflowing bucket measurements (kg)	Outflow Volume (litres)
11	0.1	24	0.2	NM	45
15	0.1	24	0.05	NM	3.8
23	0.1	24	1.4	NM	17
21M	0.1	48	0.1	0.2	110
17	0.08	48	7.9	5.1	145
19	0.1	100	5–8	>4.1	359
16	0.25	24	11.3	>5.3	250
18	0.25	48	6	3.6–5.4	530
22M	0.25	48	12.5	10.4***	460
27MC	0.25	48	5.4	1.5	651
28MC	0.25	48	0.45	<0.1**	540
29	0.25	48	3.5	3.7	604
24+	0.5	24	7.5	15.4*	NM
20	0.5	100	25–30	34.5	2,700

* Based on erosion measured at 4.5 h into test and assumes constant rate of erosion.

** Does not include material lost in first 2.5 h of outflow from test.

*** Based on average of erosion rate measured at 34–48 h into test.

+ Test developed leakage from unmonitored location at ~7.5 h into test, erosion and materials lost are estimates only.

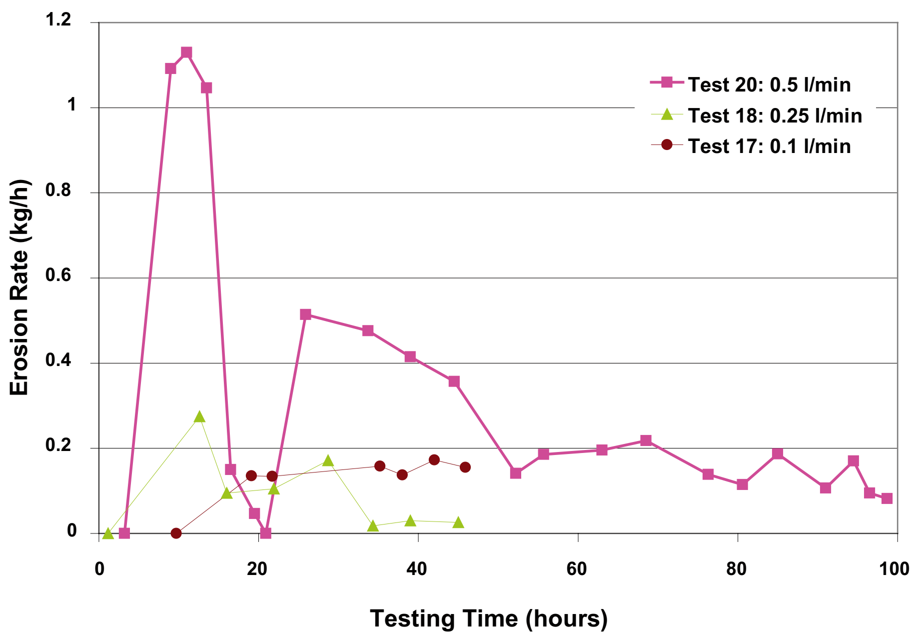


Figure 7-11. Change in erosion rate with time.

several hours, removing more than 1 kg/h of mass from the backfill (0.3% of pellets per hour). Development of flow paths through the block materials would likely result in even more erosive conditions. Where flow developed along the pellet-concrete contact the erosion rate observed showed considerable reduction, trending towards a steady-state erosive rate in the order of 0.1 to 0.2 kg/h. This suggests that the erosion is a time-dependent process.

It should also be noted that the location of the flow channel had a discernible effect on the erosion rate observed. Where the water exited the front face in a location where it subsequently flowed vertically down the Friedland block face, there was a higher degree of material removal. Friedland clay was much less resistant to the action of water flowing over its surface than the bentonite pellets. As a result the eroded mass could be increased as the result of erosion from the front face rather than internal erosion. Ultimately, the quantity of material that would need to be dealt with at the downstream face of a backfilled volume would not change but the source of the eroded mass will differ and how it would need to be handled might differ.

Although the data is limited there also appears to be higher total erosion for a given flow rate in systems where the gap between the blocks and the outside wall is filled with crushed or granulated bentonite rather than pellet materials (Figure 7-12). The reason is not clear but could be related to the wider range of particle sizes present (more fines) as well as rougher surfaces that could be more readily eroded. This influence of bentonite texture on erosion could be important if erosive action is deemed likely or to persist for an extended time.

7.5 Physical stability of block assemblies

A major concern in any backfilling operations and especially ones where interruptions in operations resulting in periods of time when the backfilled region may be left unsupported is the physical stability of the volume already filled. With the movement of water into (and perhaps through) the backfill there will be the development of swelling pressure-induced forces acting on the backfill. This together with possibly erosive activity as the result of through-flowing water could result in considerable reduction in the physical stability of the downstream face of the backfilled volume, especially in a system such as a block and pellet backfill where near-vertical faces will exist.

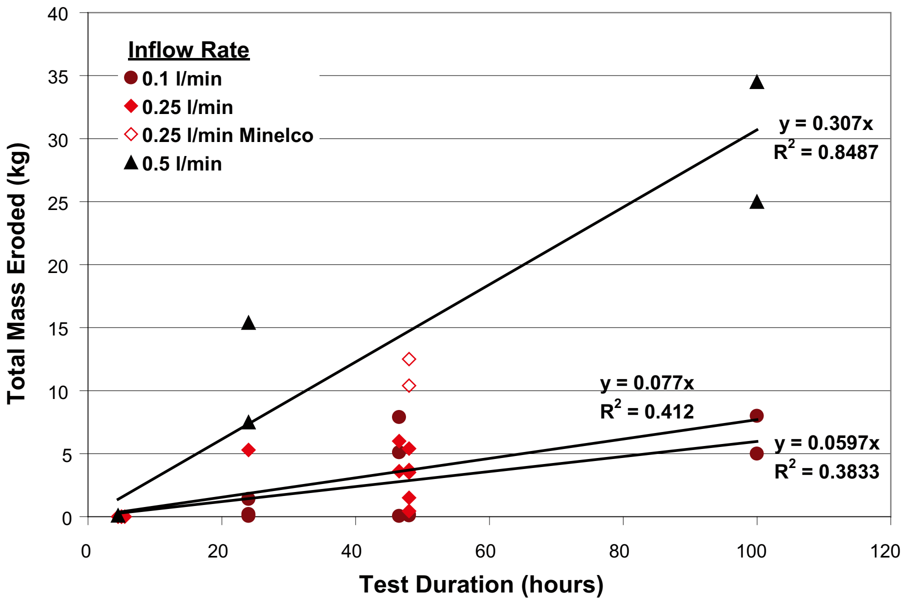


Figure 7-12. Role of time and inflow rate on quantity of material eroded.

Table 7-2. Summary of water inflow/outflow and time for outflow to occur.

	Test Duration (h:min)	Time to Outflow [h:min]	Outflow to Collection System [h]	Uptake Before Outflow [h]	Total Inflow Volume [l]	Inflow After Break Through [l]	Total Outflow [l]	Water Uptake Or Loss [l]
Test 7: @ 0.01 l/min **	118	NM	NM	NM	70.8	NM	NM	NM
Test 8: @ 0.03 l/min **	118	NM	NM	NM	212.4	NM	NM	NM
0.1 l/min								
Test 9: Slots	24	>3<20	NM	NM	144	NM	NM	NM
Test 23: Floor	24	2	2.04	12	144	126.5	17	127
Test 11: Slots	24	>3<13	13	76	144	65.3	45	99
Test 15:	24	6	7.15	42	144	99.2	3.8	140.2
Test 3:	46.5	>2<16	NM	NM	251.1	NM	NM	NM
Test 4: @0.09 l/min	46.5	>2<16	NM	NM	251.1	NM	NM	NM
Test 17:	48	2:50	9.68	48	230	187	145	85
Test 21: Minelco	48	>8<24	9	45	288	197.9	110	178
Test 19:	100	4:55	9.55	58	600	545.5	359	241
0.25 l/min								
Test 6:	5	2	4.03	61	75	14.6	0.75	74.25
Test 12: Slots	5:30	1.5	1.83	28	82.5	55	0.12	82.4
Test 10: Slots	5:30	2	2	32	82.5	51	15	67.5
Test 14:	5	5	5.13	77	75	0.0	0	75
Test 16:	24	6:20	6.8	102	360	257.1	250	110
Test 18:	48	1:10	1.15	17	720	698.8	530	190
Test 22: Minelco	48	>4<5	6.58	99	720	621.7	460	260
Test 27: Mixed*	48	3	NM	NM	720	675	651	69
Test 28: Mixed*	48	7:05	NM	NM	720	613.8	540	180
Test 29: Mixed*	48	1:18	NM	NM	720	700.5	604	116
0.5 l/min								
Test 13:	5	0:44	1	27	150	127.2	39.1	110.9
Test 24: Floor	24	0:03	0.05	2	720	709.1	NM	NM
Test 20:	100	2:40	3.2	97	3,000	2,925.9	2,700	300
1.0 l/min								
Test 5:	4:30	0:08	0.13	9	270	248	106	164

* Test composed of granular bentonite below blocks and pellet materials between blocks and concrete tube.

** Deformation in cell base resulted in loss of outflow readings.

While not a major goal of this study, the tests undertaken have provided some indications as to possible interactions within the backfill. The tests undertaken as part of this study were all provided with substantial physical support at their downstream face (excepting Tests 1 and 2), although water escape was unhindered. Four tests (Tests 9 through 12) were constructed with intentionally large spacing between block sections to see what effect this type of construction flaw would have on water movement and mechanical evolution of the system. Figure 7-13 shows how effectively the swelling of the pellet materials was in causing the vertical joints to close, providing confidence that such features could be closed in a repository environment.

Test 2 clearly showed that there is a need for a filling material between the clay blocks and the concrete (rock) walls, otherwise there will be ongoing disintegration of the system as the result of water contacting the system. This mechanical degradation includes both slumping and erosion of the clay blocks but also loss of mechanical strength in the blocks as the result of ongoing water uptake (saturated materials have lower strength than unsaturated materials at the water contents examined in this study). This is particularly important at the base of the clay block assembly where loss of mechanical strength results in compressive failure of the laterally unrestrained blocks and subsequent tilting and slumping of the block assembly (photographs showing this are provided in Appendix A).

The presence of a granular or pellet fill material between the blocks and the walls of the test resulted in a much more stable system although the result was redirection of the swelling-induced strains and forces toward the face with least resistance to deformation (front face). The result was the development of considerable force on the steel grid at the front (resulting in deformation of the grid in the first two restrained tests (Test 3 and Test 4). In subsequent tests the clay tended to extrude into and through the mesh of the restraint system. These swelling-induced forces did however act to compress the clay block assemblies, resulting in closure of the gaps between rows of blocks as previously described.

Where there was some degree of freedom of movement between the blocks and the restraint system the result was sometimes an expansion of the outermost rows of blocks and development of wedge-like openings between vertical sections of blocks. Figure 7-14 illustrates this type of deformation and the effects on the front face of the assembly. The outwards tilting of the blocks due to mechanical deformation makes worse the effects of reduced strength in the blocks as the result of water uptake and block swelling at the downstream face (dark regions) that are evidenced by the vertical cracking of the blocks. This type of wedging and slumping behaviour would ultimately result in the mechanical failure of the downstream section of the backfill, exposing regions upstream to an increased potential for contact with water.

These tests show the importance of providing lateral (through pellets/granular) and vertical support to the backfill. The vertical support can be provided by ongoing placement of backfill such that the newer materials effectively restrain the previously placed materials or else if operations are to be interrupted then some form of temporary vertical support needs to be provided. In addition, it should be considered what type of block installation pattern (layout) provides the best mechanical stability for the block assembly.

Figure 7-13. *Closure of vertical construction gaps in Tests 9, 10.*

Figure 7-14. *Deformation of block assembly due to swelling-induced forces.*

8 Summary

A total of 27 tests were successfully completed as part of a study of water uptake patterns by, the manner in which water will move through, the erosion of clay from and the physical stability of block – pellet/granular backfill. Variables such as inflow rate, inflow duration, inflow location and the type of material used to fill the space between the clay blocks and the cell walls and floors were also examined.

The scale of these tests was considerably larger than have previously been attempted and represent a step towards conduct of backfilling evaluations at scales representative of field conditions but where boundary conditions can be controlled to facilitate system evaluation. It should be noted that the conclusions drawn from these tests are for the scale of test done in this study, the influence of test dimension and variations in flow path length were not evaluated. These tests do however provide valuable guidance to the planning for the conduct of the ½-Scale simulations planned for completion in 2008. These larger-scale tests will allow time, dimension, inflow rate and flow path length to be evaluated and compared to the results of the tests described in this document.

There are a number of conclusions that can be drawn from the results of the tests done as part of this study, they include the following:

1. In a system where water inflow occurs at a rate of 0.1 l/min (6 l/h) or higher, there is a need to provide block backfill materials with a material to fill the space between it and the surrounding rock. If this is not done in a timely manner then there is a substantial risk for block slumping and backfill disruption.
2. The presence of construction defects (gaps between blocks or groups of blocks) did not affect the behaviour of the backfill system, swelling pressure developed by the surrounding bentonite pellets or granules resulted in closure of these gaps. The larger-than-normal construction gaps or joints did not tend to be preferential pathways for water movement.
3. Water uptake patterns by the clay block – pellet/granular backfill systems were initially controlled by the inflow rate. High inflow rates generally resulted in rapid filling of the larger pore spaces of the nearby pellet/granule materials followed by swelling of these materials. As the filler materials swelled they provided more resistance to water inflow and encouraged inflowing water to find pathways that offered lower resistance to further water influx. These generally were in the form first of flow along the pellet-block contacts and then as the pellets swelled, discrete flow paths and channels formed at the concrete – pellet/granule interface. Once channels were established water moved rapidly and directly from the point of inflow out to the downstream face of the test assembly. These preferential perimeter flow paths typically showed limited erosive potential and the quantity of material removed per unit time decreased substantially, as did the rate of water uptake by the system.
4. There were indications in the limited number of tests conducted in this study of a higher rate of erosion in systems constructed using the granular bentonite (Minelco) as opposed to pellet (Cebogel) materials when water inflow rate was 0.25 l/min or higher.
5. The ratio of total mass of eroded material to total water inflow was 35 g/l and was apparently largely independent of the water inflow rate (where flow >0.1 l/min). In addition there is a tendency for this ratio to decrease with time. This may be due to flushing of the pellets fines in the beginning of the tests and formation of non-erosive flow paths to the pellet-rock interface.
6. Internal (within block assembly), flow paths developed in several of the tests done as part of this study. There was no clear linkage between their development and the water inflow rate and any test done with a flow rate in excess of 0.1 l/min could experience this phenom-

enon. Once established, ongoing erosive flow occurred through the clay block assemblies and they did not subsequently close (over duration of these tests).

7. Substantial quantities of clay materials can be removed at relatively low water inflow rates. This is particularly true if the system manages to develop an internal flow path that passes through the Friedland clay block materials. The clay blocks provided little resistance to flow and were prone to much higher erosion rates than the pellet/granular material. Therefore the location of the flow path is considered as an important factor influencing the magnitude of erosion in block backfill.
8. Conditions that lead to internal erosive pathways developing are unclear and may be relatively random (water finds a pathway to blocks at early stage and flow path remains open). The tests described in this document were not able to identify any condition or mechanism that would lead to formation or (self-healing) non-formation of internal flow paths (excepting if inflow rate was less than 0.1 l/m where water was not able to move effectively through the pellets and into the block materials).
9. The location of water entry into the test appears to be important to system evolution. Tests where water entered the base of the cell showed rapid movement of water towards the face of the test along the block-granule interface with limited wetting of surrounding materials. This flow path was typically erosive in nature with a substantial quantity of granular material being removed from a limited volume of backfill. Where flow towards the face of the test cell was restricted (due to swelling of granules and plugging of flow path?), water was observed to move upwards into the clay block materials, developing a persistent and erosive channel through the blocks and pellet fill materials. Tests supplied with water from a position partway up the wall of the cell tended to be less prone to development of highly erosive flow paths and a greater quantity of water entered the system before it exited the front face of the block assembly.
10. Water supplied from locations above the floor of the cell did not tend to move towards the opposite side of the cell. Flow path(s) generally remained on the same side as water entry occurred with entry into the materials located below the block assembly being particularly problematic. The result is a tendency for the materials below the blocks and the lower portions of the block assembly to remain dry.

These tests have provided the basis for the design of much larger (1/2-tunnel scale), simulations planned for completion in 2008. Factors such as flow path length and inflow rates indicate that given the larger volume of pellets/granular fill in the ½-scale as well as in an actual tunnel, it is unlikely that inflow rates of 0.1 l/min are going to be problematic. At rates in excess of 0.1 l/min there are indications that piping and erosive behaviour may develop. However, the consequences of this erosion on the (resulting average dry density of the backfill) are clearly scale- and time-dependent since one unit of water can transport only a limited amount of sediments and the erosion seems to decrease in time. This remains to be verified with the half-scale tests. Due to the scale-effect, the accepted water inflow into a tunnel can be different for the Swedish and Finnish deposition tunnels. However, taking into account the practical point of view, as-small-as possible a localized water inflow rate (e.g. < 0.1 l/min) is of course preferred. There will also need to be some form of temporary restraint system available during repository backfilling operations that will provide support to the system during periods when a pause in material placement occurs. This restraint system need not be watertight but will need to be able to prevent slumping of the front face of the backfilled tunnel. Of particular importance is the clear tendency of water entering the tunnel to move towards the downstream face of the backfill long before the macrovoids present in the pellet fill have reached saturation. There will therefore be a need to have a means of handling the exiting water during backfilling operations as well as some means of mitigating water inflow for a brief period while backfilling is ongoing.

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Appendix A

Detailed description of tests and interpretation of results

The conduct of the 27 Tests completed in this study included comprehensive observation and monitoring at all stages of their operation. As described briefly in the main text of this report, parameters such as inflow resistance, water conduction, water distribution at the end of test, photography and sampling were all recorded.

This appendix provides the detailed records and assessment of these tests. A brief synopsis of the results is presented in the main text of this report.

The tests done as part of this study are presented on the basis of the water inflow rate set for each test. This allows for evaluation of how this key parameter has affected the water uptake and distribution patterns for block and pellet assemblies. Beyond the distribution of the water and its outflow characteristics the resistance to water influx during the test was monitored for most of the tests. This information is important with regards to how water moves into backfilled volumes and how effectively the backfilled volumes are in resisting influx immediately following its installation. Table 3- provided the inflow rates applied to each of the tests undertaken in this study and the observations made for each test are provided below in terms of their inflow rate. Table A-1 provides a summary of the masses of block, pellet and granular materials used in each of the tests done as part of this study as well as the estimated pre-test densities of the installed materials. Based on this data, the block filling degree (volume of blocks versus total volume of the test setup) was 61.6-65.8%. The average thickness of the pellet filled zone varied between 0.1 and 0.2 m, depending on the location but was never less than 0.1 m.

Much of the information gained in the course of these tests is derived from visual observations made during testing (points of water outflow, water distribution observed at the time of dismantling). As a result there was extensive photographic recording of conditions and these photographs are used extensively in this document. In many cases the photographs are modified through the addition of highlighting lines to enable the reader to readily pick out significant features that are discussed in the text.

A1.1 Block assemblies with no pellets present: Tests 1 and 2

Before tests containing block assemblies and surrounding pellet materials were installed two preliminary tests to examine block interaction with a moist atmosphere where there was no liquid water influx (e.g. a dry tunnel section) and where water dripped directly onto the surface of a block assembly (as it would be prior to pellet installation) were undertaken.

Each test consisted of 108 clay blocks assembled in a chamber having a high relative humidity environment. Six layers of 18 blocks each were assembled into a cube of 0.9 m by 0.9 m by 0.45 m. Each layer was rotated 90 degrees in order to provide a more stable assembly. Figure A-1 shows the test as it was constructed (it should be noted that the darker layer present in the lower portions of the block assembly is the result of shadowing not a difference in the materials). The block assembly was placed on a stiff steel mesh that allowed for air movement.

Table A-1. Masses and densities of materials installed.

Test #	Volume of Each Test (l)	# Blocks Per Test	Mass of Blocks* Per Test (kg)	Volume Of Blocks Per Test (l)	Mass of Pellets Per Test (kg)	Volume Of Pellet Fill (l)	Bulk Density of Pellets** (kg/m^3)	Pore Volume of Pellet Fill (l)	Dry Pores In Pellet Fill+ (l)	Dry Density of Pellets (kg/m^3)
3,4	942.3	172	1,126.3	580.5	485	361.8	1,340	210.4	133.3	1,130
5,6	942.3	178	1,169.5	600.8	475	339.9	1,400	191.4	115.9	1,180
7,8	942.3	178	1,165.5	600.8	467.5	341.5	1,370	196	121.7	1,150
9,10	942.3	178	1,165.5	600.8	462.5	341.5	1,350	197.3	123.7	1,140
11,12	942.3	176	1,152.5	594	367.5	312.4	1,180	197.9	139.5	990
13,14	942.3	184	1,204.8	621	405	312.4	1,260	189.8	125.4	1,060
15,16	942.3	184	1,172.1	621	430	321.3	1,270	204	135.6	1,070
17,18	942.3	184	1,204.8	621	415	312.4	1,330	191.6	125.6	1,090
19,20	942.3	184	1,204.8	621	410	312.4	1,310	184	118.9	1,110
21,22	852	164	1,073.9	553.5	390	298.5	1,310	231.3	169.3	1,100
23,24	852	164	1,073.9	553.5	455	298.5	1,290	210.4	138.1	1,090
27,28	904.4	164	1,073.9	553.5	260/156.25[++]	352.9	1,180	223.2	157.1	990
29	942.4	184	1,204.8	621	275/156.25[++]	312.4	1,380	178.1	109.5	1,160

Values determined per test pair, averaging total mass installed for two tests)

* Blocks had an initial average bulk density of 1,940 kg/m^3 and water content of 6.3%.

** Pellets and granules both had an average pre-test water content of 18.7% and are assumed to have a bulk density of 2,100 kg/m^3

[+] Based on total pellet porosity less water present in pellets at start of test.

[++] Values represent quantities of Cebogel pellets and Minelco granules used in tests

Figure A-1. *As-Built Test #1.*

In Test 1 there was no attempt to control the humidity around the blocks beyond the natural high humidity conditions present underground at Äspö. The open face of the test cell was loosely closed with a Plexiglas sheet in order to limit the effects of air currents and short-term humidity variations in the test location. The humidity and temperature within the test cell was monitored using relative humidity sensors. Humidity ranged from 92% to 98% and temperature ranged from 17.4 to 19.3 C. There were no obvious volumetric changes to the individual blocks or the block assembly over the course of the test although the control block did exhibit measurable expansion.

This experimental set-up provides one extreme of the range of conditions that may exist within a backfilled tunnel: a situation where there is no liquid water influx but the high relative humidity of an underground environment is present. The manner in which the blocks interact with this environment provides valuable information regarding the evolution of the backfill in a dry section of tunnel.

A1.1.1 Test 1

At the time of disassembling this test, 38 days after its installation, measurements of the breadth and width of the assembly was made and a visual inspection was made (Figure A-2). The block assembly was assigned a numbering system that allowed each block to be individually located. A number of the blocks in the lowermost layer showed cracking that went beyond the normally observed surface features. As can be seen in Figure A-3, these cracks were generally on the outermost face of the blocks. They may be attributed to localized stresses on the outer edges of the blocks due to slight deformation of the underlying steel mesh. The region at the centre of the block assembly would have experienced the greatest load and hence may have deformed somewhat, inducing localized stresses in the outermost block edges. Given the very low strength of the blocks used it would likely not have required much load to induce edge failures. This type of “failure” feature is not dissimilar to those observed in Humidity Test #2 and highlights the importance of using backfill materials of sufficient strength to support the entire load induced by the blocks.

In the course of dismantling this test samples were recovered in order to determine what water content and density changes had occurred in various areas of the block assembly. Of the samples recovered, the highest water contents (defined as 100 x mass of water/mass of dry soil) were present in the upper and lower horizontal surfaces as well as the corners of the block assembly. A clear water content gradient through the block assembly was still present after 38 days and proximity to the open atmosphere clearly affected water uptake. The corners, where the greatest surface area was available for water uptake showed the highest water content at the end of the

(a) Outer Face of Assembly b) Mid-Depth of Assembly

Figure A-2. Block assembly at time of dismantling. (Note block numbering and chipping of faces).

Figure A-3. Cracks in surface of lowermost blocks.

test (typically > 9%) while the core of the assembly showed approximately the same water content as was present at the time of construction (approximately 6.5%). Despite the presence of small spaces between the individual blocks, the core of the assembly remained in its as-placed state.

The data collected also indicates that the overall density of the blocks decreased approximately 6% over the course of the test. The overall volume change in the assembly was measured to be approximately 2% expansion (as measured immediately before disassembly), consistent with the average increase in individual block dimensions of 2.8%. The width and breadth of the assembly at the time of dismantling measured 911 mm by 906 mm (± 1 mm) whereas the original assembly was 900 mm by 900 mm (plus very small construction gaps). Regardless of the presence of small construction joints the overall difference between the initial and final dimensions are too large to attribute to construction joints only. The assembly experienced a slight increase in volume and reduction in dry density as a result of water uptake from the atmosphere.

This simulation provided valuable information regarding the manner in which a clay block assembly will respond to a humid environment. The water vapour clearly entered the outer regions of the assembly and was adsorbed by the clay but beyond the "skin" regions, did not move into the block assembly. This can be described in terms of changes in the suction potential. Once the relatively high suction originally present at the outermost block surfaces had been satisfied by the water vapour, the suction gradient decreased and water movement into the assembly was limited to what could move through the pore spaces of the outer skin of the blocks. It should be noted that the blocks used in this test were neither as dense or as close to full water saturation as is proposed for backfill block materials proposed for repository use making their rate of water uptake from the atmosphere different than would be observed in denser materials. Despite the density differences between the tested and proposed materials this test has demonstrated that blocks of inferior quality were able to effectively limit water vapour penetration into the core of a backfill block assembly.

The outer blocks were still physically stable at the time of disassembly although small, shallow, spalling-type failures were observed on the faces of some blocks. This is again largely attributed to decrease in suction in the near-surface regions and subsequent reduction in the strength of the blocks although localized tensile loading conditions may also have contributed to the damage observed. It is anticipated that in block materials of higher density and degree of saturation that the mechanical stability and self-sealing ability should be better than was observed in this simulation.

A1.1.2 Test 2: Water dripping directly on top of clay block assembly

Test 2 exposed precompacted clay blocks to a constant 0.01 l/min water influx directly onto their surface. This test was used to simulate a situation here blocks had been placed but pellet installation had not yet occurred.

108 clay blocks were assembled on top of a layer of coarse bentonite granules (Minelco) in the same chamber used for Test 1. Test 2 differed in construction from Test 1 in that coarsely crushed bentonite (Minelco) was installed below the blocks, simulating a base of the type being considered for use in a tunnel. Water (natural formation water taken directly from fracture HD0025A at the Äspö HRL (salt content (NaCl) of approximately 0.5%)) was supplied at 0.01 l/min from a height of 0.03 m above the surface of the blocks at the centre point of the upper surface. Water was supplied to and allowed to seek its own path from this location. Over the 9 days that this test operated approximately 1,300 litres of water was supplied to the test

It should also be noted that the clay blocks and bentonite granules were not provided with any confinement and so any swelling or water-induced deformation of the system was not constrained. This geometry was intentionally chosen as it provides a very conservative set-up for testing. Although it is anticipated that the backfilled tunnel would have some filler material almost immediately placed between the clay blocks and the surrounding rock an unscheduled interruption in backfilling caused, for example by equipment failure might result in a section of partially-backfilled tunnel being left for a period of time. Additionally, it examines the situation where pellet-filling is not done as part of regular operations, establishing that block and pellet-placement must be done in as close to a continuous manner as possible.

Operation, dismantling and laboratory analyses

The test was started with a water inflow rate of 0.01 l/min as shown in Figure A-4 where water dripped onto the upper surface of the block assembly. In Figure A-4 the almost immediate swelling of the upper surface of the block can also be seen, this effectively sealed the surface for substantial water absorption into the blocks at the top of the assembly. The low permeability of the clay is further illustrated by the pooling of this water on the upper surface of the block. Very soon after the start of water inflow the water began to move across the top of the block assembly towards the right-hand side of the assembly. This was the result of a small inclination of the assembly and provided a reasonable simulation to what might be encountered in a tunnel situation where installation of a completely level assembly will be problematic.

After only a few minutes of water supply the clay at the site of water contact had swelled upwards by approximately 5 mm as shown in Figure A-5. With swelling, the pathway for subsequent water movement changed as it sought to flow away from the inlet point. This resulted in an increasingly large wetted area but still a tendency to move downslope on the upper surface of the blocks.

Figure A-4. *Water supply to and rapid swelling of clay (note swelling of clay and pooling of water above it).*

7 hours into test

Figure A-5. *Water and eroded clay flowing down the side of Test 2 (note also the swelling of clay blocks on left side of photo cause water to flow to right).*

After only a few hours of operation, the water reached the right side of the block assembly (Figure A-5) and the clay started to swell laterally, softening the outer corner of the stack, leading to erosion of clay. Additionally, the lateral displacement of the hydrating blocks results in an unsupported mass developing along the edge of the block. This material being subject to gravitational effects and its very high water content (liquid limit) means that the forces holding the very soft clay together are small (low tensile strength), experiences slumping of the hydrated blocks which further contributed to the erosive action of flowing water.

During the test different flow paths for the water formed as the result of how the surface changed during hydration-induced swelling. When the top surface of the stack swells, water is diverted from its current flow path and must find a new path to follow. This resulted in different areas of the top of the block assembly being supplied with water at different times. Figure A-6 shows an example of this, the area on the left-hand side of the photograph is no longer receiving water but the right-hand side is (as evidenced by the shiny surface on the left-hand side).

After 77 hours some of the hydrated clay had flowed down to the floor of the test cell and over the edge of the tray onto the platform below it (Figure A-7a). This was occurring on all of the sides of the block assembly excepting for the left side were the water did not reach. At this stage essentially no water was reaching the base of the assembly where the Minelco granules were located, with the water being taken up by the clay blocks or else was bypassing the pellets due to overlying hydrated block materials (as can be seen at the face of the block assembly in Figure A-7b).

Figure A-6. Erosion of block assembly (24 hours after start) (extensive swelling of clay and slumping from top of assembly).

By the time that 144 hours of operation had passed, the granules and blocks in the bottom layer had at begun to take up water and swell (Figure A-7b), filling much of the volume between the lowermost layer of blocks and the tray wall. This hydration was accompanied by the development of cracks in the blocks in the bottom layers and a clear hydration of the lowermost layer of blocks (Figure A-8), seen as the dark region below still dry blocks. The cracking was likely the result of the reduced strength of the block material as its degree of hydration increased. At the end of 9 days of testing the block assembly had undergone considerable slumping failure (Figure A-7c).

Inflow of water was discontinued about 3 hours before disassembling started. The block assembly had at this stage had experienced considerable erosion on all the sides except for the left (high side). Figure A-7c shows the test immediately prior to disassembly and of particular note is the lateral displacement of the layer of blocks on the upper left side.

Despite the extremely eroded and slumped appearance of the test at the time of decommissioning (Figure A-7c) there was actually only a limited portion of the block assembly that had experienced substantial disruption. For the most part, water had penetrated only 1 block thickness into the assembly and the outermost blocks in contact with water had swelled and slumped to give the appearance of a massively disrupted system.

(a) 77 hours (b) 144 hours (c) 210 hours

Figure A-7. Block assembly at 77, 144 and 210 hours.

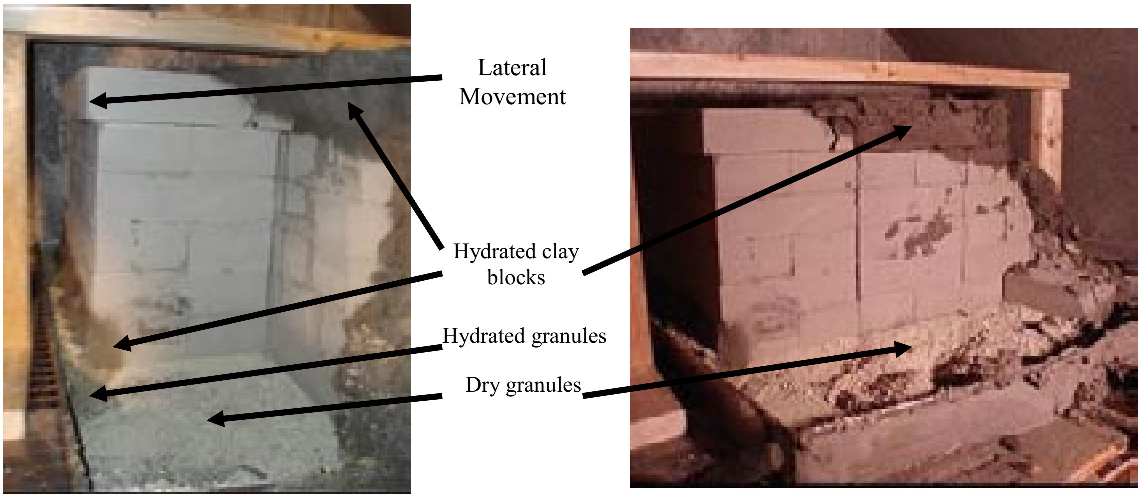
Figure A-8. *Wetting of the granules and base of blocks (144 hours) (note lower layer of wet blocks and their deformation due to mass of overlying material).*

Dismantling began with the portion of the test that had apparently undergone the least amount of disruption (left side) in the course of testing. Figure A-9 shows the conditions present once the front-left corner had been removed. At some time following the beginning of hydration, a gap existed between two columns of blocks (either because the space between the columns did not close immediately or else as the result of the swelling of the blocks leading to movement and opening of a joint) in top layer of the stack. This opening has caused some water to leak into the stack along a limited length of the assembly as can be seen in Figure A-9. This leakage occurred for only a short time, likely early in the test, as there is evidence of only a small amount of hydration along the plane of seepage and no water uptake in the underlying granular material. Figure A-9 also shows the hydration pattern at the base of the assembly where water is absorbed from the granular bentonite into the block materials.

With removal of the front half of the test to 0.3-m-depth and exposure of the materials directly beneath the water inlet it was observed that only the block immediately below the water inflow point had experienced extensive wetting (Figure A-9b). To the right of the central blocks the water has intruded as deep as the second layer. This deeper intrusion of water can be explained due to opening of gaps and cracks that allowed water to get inside or else the longer duration of water flow on the surface of this region.

The Minelco granules and the Friedland blocks have been hydrated in the area of the space between the blocks and the tray as illustrated in Figure A-9 and Figure A-10. This wetting was the result of water running down the slumped block faces and accumulating in the floor of the tray containing the test. The granulated material rapidly formed a saturated skin of swollen bentonite that resulted in water pooling and movement around the base of the test. This resulted in water uptake by both the bentonite granules as well as the clay blocks in contact with the free water. The wetting front moved approximately 3 cm horizontally into the clay blocks and underlying bentonite granules. The wetting front in the granules was sharp, as can be seen in Figure A-10a.

Removal of the 0.6-m depth of block materials was done without finding any further features of note until the lowermost layer of blocks was exposed (Figure A-11). This layer showed no signs of water uptake by the block assembly beyond the outer edges (3–5 cm) as shown in Figure A-10. Cracks were present in the originally intact blocks at the perimeter of the block assembly as shown in Figure A-10 and Figure A-11. These cracks were most evident in the region where water uptake had occurred and as a result the strength of the blocks had been reduced to the point where mechanical failure due to the overlying mass of the block assembly began.



(a) Left side 0.3m x 0.3m removed (b) Front face removed to 0.3m depth

Figure A-9. *Disassembling the front of Test 2 to depth of 0.3 m.*

(a) Left side of assembly (b) Right side of assembly

Figure A-10. *Contact between clay blocks and granular bentonite.*

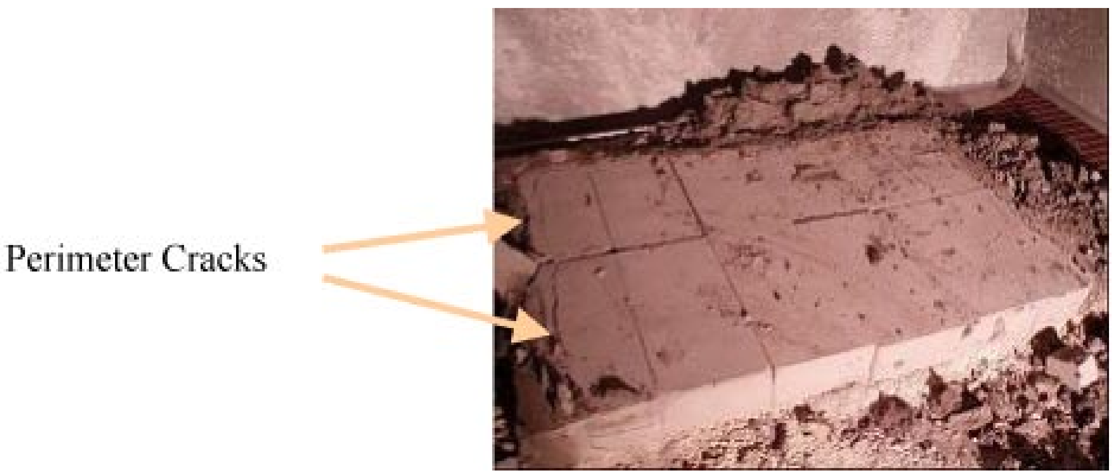


Figure A-11. *Bottom layer of block assembly showing cracking of wet blocks.*

A number of samples were recovered in order to determine the changes that had occurred in various areas of the block assembly. Table A-2 presents the results of water content analyses done on these samples and Table A-3 the density information obtained from archived and recovered block materials.

The two block samples recovered from the central portions of the block assembly did not show any changes in water content (Table A-3). This supports the visual observations made that concluded that this region was unaffected by the water supplied to the block surface.

The Minelco granules in the channel between the blocks and the side of the tray had a very high water content, due to the presence of standing water in this region for a considerable portion of the test (Table A-2). As a result of this effectively unlimited supply of water the granules were able to take on as much water as they wanted. The granular material sample taken from beneath the blocks (sample 3 in Table A-2) had approximately the same water content as the reference material (as dry as at the start of the test). This indicates that the granules at the outer portions of the tray were able to swell quite rapidly, providing an effective barrier to further water intrusion below the blocks.

This simulation provided valuable information about how water will move in the vicinity of an unconfined clay block assembly. For the most part the water rapidly caused hydration of the outer surfaces of the blocks, effectively sealing the core of the block assembly from rapid hydration. Once the block surfaces had hydrated and sealed water was forced to run across its surface until it flowed down the outermost vertical faces of the block assembly.

Hydration of the vertical surfaces and swelling of the upper layer of blocks led to a weaker region along the hydrated surfaces and swelling of the upper layer of blocks led to a combination of erosive and tensile failure of the edges of the blocks. This resulted in slumping of materials from the assembly and what appeared to be substantial loss of materials from the original block volume. There was actually relatively limited loss of materials beyond the outermost, hydrated blocks as the clay swelling resulted in a substantial volume change in the eroded materials and also provided a low permeability "skin" that protected the interior portions from further erosion. Despite the differences present between the tested and proposed materials (lower density blocks tested), the results of this test are important. They have demonstrated that blocks of inferior quality were able to effectively self-seal and remained quite stable despite the complete lack of restraint or support. It is anticipated that in block materials of higher density and degree of saturation that the stability and self-sealing ability should be better than was observed in this simulation.

Table A-2. Water content measurements from Test 2.

Sample	Water content*
Block 1 (Reference Friedland block)	6,7%
Block 2 (Reference Friedland block)	6,4%
Block from disassembling (outer part)	6,6%
Block from disassembling (inner part)	6,6%
Wetted Friedland clay block	76,9%
Wetted Friedland clay block	44,1%
Wetted Friedland clay block	61,6%
Minelco granules (Reference)	18,7%
2 (Minelco granules from wet area)	138,6%
3 (Minelco granules from dry area)	19,4%

* (mass of water divided by mass of dry material) x 100

Table A-3. Bulk and dry density of Friedland clay blocks in Test 2.

Sample	Bulk Density (kg/m³)	Dry Density (kg/m³)
Block 1 (Reference block)	1,910	1,790
Block 2 (Reference block)	1,930	1,810
Block from disassembling (outer part)	1,940	1,820
Block from disassembling (inner part)	1,940	1,820

It is also important to note that at the flow rate examined in this test (0.1 l/min) and the very small gaps between the blocks, the gaps between the blocks sealed quickly, preventing water from flowing inwards to the core of the block assembly. If larger gaps had existed between the blocks or water inflow had occurred immediately at a joint, a very different scenario would likely have developed as substantial water would have been able to enter, essentially unhindered to the core of the block assembly or else have had a pre-existing constrained flow path along which it could move and potential erode materials. This would also have induced internal swelling, potentially resulting in structural disruption of the assembly (as observed in movement of upper left-side blocks in Test 2 (Figure A-9).

Finally, it should again be noted that Tests 1 and 2 do not represent situations that are anticipated to be encountered in a normally-operating backfilling process where blocks and pellets are installed in as continuous and continuous process as possible. These tests are intended to provide a demonstration of what might happen in an upset situation where backfilling operations are disrupted for some reason.

A1.2 Tests having water inflow of less than 0.1 l/min

Of the tests undertaken as part of this study only two had water inflow rates less than a nominal value of 0.1 l/min. These tests were intended to provide some bounding information on the behaviour of the backfilled tunnel under conditions of very low localized groundwater inflow. These tests were run at inflow rates of 0.01 l/min (Test 7) and 0.03 l/min (Test 8) and the results are described below. These tests operated for approximately 120 hours with a constant rate of water influx provided to each. The resistance to water inflow were also monitored for this test, providing a measure of what degree of self-plugging this geometry and inflow rate would provide to the backfill over the very short-term.

A1.2.1 Test 7: 0.01 l/min for 120 hours

Test 7 consisted of 1,165.5 kg Friedland clay block materials and 485 kg of Cebogel pellets installed in a 0.942 m^3 test chamber. The pellet-filled volume had a dry density of 1,150 kg/m^3. It was exposed to the lowest inflow rate of this testing program, 0.01 L/min (0.6 L/hr) and represents a situation where there is a very low conductivity hydraulic feature that intersects the tunnel excavation. It provides an opportunity to examine what effect, if any this type of feature would have on backfill behaviour during routine filling operations.

No water that had exited Test 7 at the time of its completion, all 72 litres added to the test was apparently taken into the matrix of the pellet-block system. This volume represents 37 % of the total and 59% of the originally unsaturated void volume (air-filled void volume) in the pellets. Figure A-12 presents the water distribution patterns within this test, clearly showing that at this very low rate of water influx, water is taken up quite uniformly by the clay pellets with small quantities beginning to enter the clay blocks in the core of the assembly. In order to highlight the visually observed features in this and subsequent tests, photographs of the faces of the test sections have been highlighted with white lines (outlining dry areas) and dark lines (showing original block perimeter). This allows for easier visual comparison of the results.

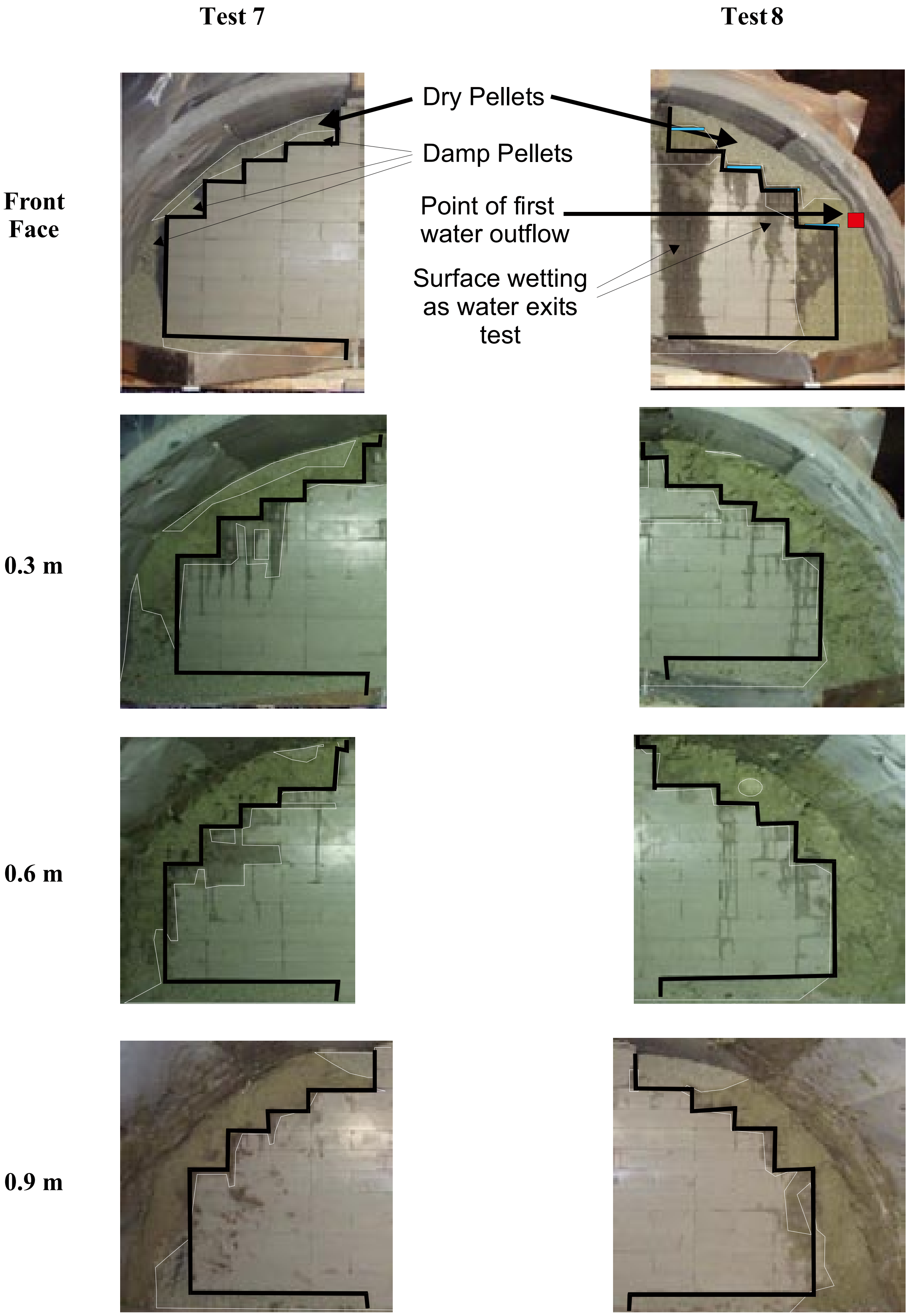


Figure A-12. *Wetting of Test 7 (0.01 l/min) and Test 8 (0.03 l/min) at 120 h. (Showing extensive water uptake by pellets when water inflow is slow).*

An inflow rate of 0.01 l/min is apparently slow enough that it would not adversely affect back-filling operations or the front face stability of the backfill installed a tunnel. Given the larger volume of pellets (and associated voids) in an actual repository tunnel it would seem likely that a point-source inflow rate of 0.01 L/hr per 1.2 m distance (length of Test 7 test assembly) of tunnel would not be problematic until a period in excess of five days had passed. Samples taken at the time of decommissioning showed that there were distinct patterns of water content and density associated with the clay pellets. It was found that the pellet materials closest to the water inlet point had the highest water content (Table A-4) Those regions further away were less wet and in some cases the dry density appeared to be slightly higher than was present at the time of construction. This might be due to slight compaction induced by the swelling of the overlying pellets.

Figure A-13 presents the resistance to water inflow monitored at the contact between the water supply line and the pellet backfilling. There is only a nominal resistance to inflow, increasing from approximately zero to 65 kPa by the end of the test. This resistance was extremely erratic showing considerable fluctuations, indicative of water finding flow-paths of low resistance that became slightly obstructed (increasing resistance) perhaps due to localized clay swelling. With increasing flow resistance the water was forced to find a new, less restricted pathway (drop in resistance). The degree of fluctuation appeared to be decreasing with time, indicating that the system was beginning to homogenize and provide a more consistent resistance to flow. Even with the increasing resistance to flow the system was not able to provide more than 65 kPa resistance to inflow even after 4 days of operation. Test 7 was run together with Test 8 (described below) and may have experienced some leakage from the water supply system in the course of its operation.

In the course of disassembling the test a limited number of samples were recovered for water content determination. These samples located as indicated by A-D in Figure 5-2 provide a rough indication of the distribution of water within the test. These data are provided in Table A-3 and indicate that the inflowing water has effectively saturated the region immediately adjacent to the inlet port as well as the vertical section immediately above and below the inlet. Water seems to have preferentially moved to the rear of the cell, once again largely filling that region (excepting base below blocks and uppermost crown). Forward from the inlet location water seems to have preferentially moved to the pellet-clay block interface and then flowed along the horizontal interface towards the front face of the test. This flow to the face seems to have dominated the system, leaving considerable volumes of pellets dry at the base, outer perimeter and crown of the test. It is likely that these regions would undergo more gradual wetting as water was drawn into them by the suction of the dry bentonite.

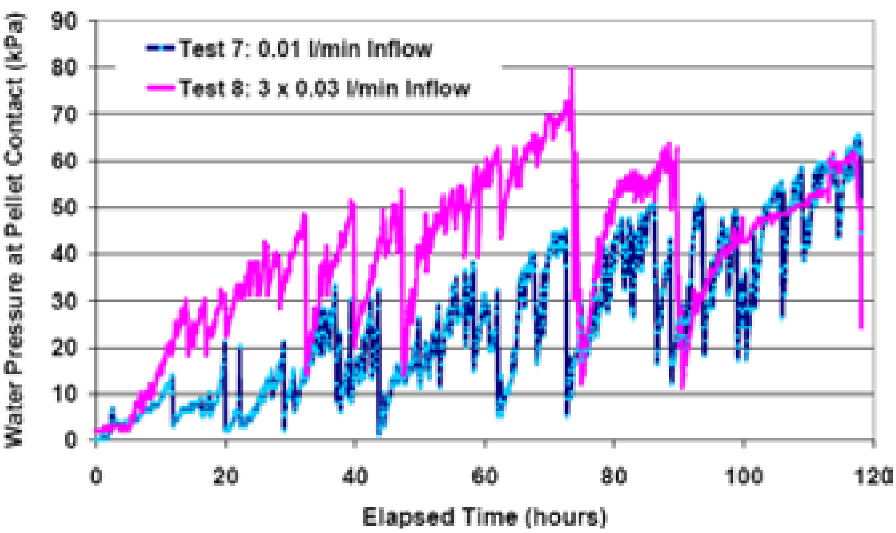


Figure A-13. *Resistance to water inflow (Test 7 and Test 8).*

Table A-4. Gravimetric water content measurements for Tests 7 and 8.

	Location*	Test 7 Water Content (%)	Test 8 Water Content (%)
Pre-test	**Pellets**	**18.9**	**18.9**
Face	A	19	19
	B	19	NM
	C	19	NM
	D	19	19
0.3-m	A	49	48
	B	62	80
	C	26	75
	D	19	19
0.6-m	A	61	65
	B	103	87
	C	57	64
	D	19	19
0.9-m	A	60	19
	B	74	68
	C	58	59
	D	19	19

* See Figure 5-1 for sampling locations
NM – not measured

A1.2.2 Test 8: 0.03 l/min for 120 hours

Test 8 was constructed from a total of 1,165.5 kg of Friedland clay blocks and 485 kg of Cebogel clay pellets were installed in the 0.942 m^3 test chamber. The inflow rate was set at 0.03 l/min (1.8 l/hr).

Unlike Test 7 this test saw water exit the system. At approximately 50 hours (90 litres water input), water was observed flowing out of the system along the top of the left-hand side of the block assembly at the interface between the blocks and the pellet fill (see Figure A-12). This flow continued for the duration of the test (an additional 70 hours). The area experiencing wetting and contributing to the outflow of water gradually increased as is evidenced by the presence of additional flow exiting from other horizontal block-pellet interfaces, highlighted by the wetted vertical face at the downstream end of the test.

Quantitative measurement of water outflow of water was difficult to monitor due to a leak in the chamber, resulting in flow between the liner installed between the clay pellets and the concrete and the concrete itself. This leakage was of indeterminate magnitude but certainly represented more than a few litres of water. The test therefore had somewhat less than 210 litres of water injected into it in 120 hours. At the time of first outflow, and prior to the start of system leakage, 90 litres of water had entered the system. This water would have occupied approximately 46% of the total pore space and 74% of the initially dry pore volume of the pellet-filled volume. Some of this water was also taken into the Friedland clay blocks, which means that the calculated pellet saturation values are higher than were actually present.

Entrained in the exiting water was a small amount of particulate material, as can be seen in Figure A-14. This material was from the bentonite pellet filling (based on colour of eroded material) and likely represents fine materials (dust) associated with the pellets. The flowing water was able to incorporate this material and carry it out of the system before it could hydrate and self-filter. The total quantity of material removed was very small and is estimated at no more than 10 grams.

Figure A-14. *Eroded bentonite pellet material in Test 8.*

At the time of test dismantling, the manner in which the inflowing water interacted with the pellets and block materials was examined. Inflowing water apparently initially moved downwards into the system until the clay had hydrated sufficiently to seal off the lowermost (basal) portion of the clay pellet fill. The water then pooled as a perched water table on the wet pellets, gradually moving inwards towards the clay block assembly as well as being drawn upwards into the pellets. The water then moved towards the front face of the test, gradually wetting the materials further away from the inlet points. A limited number of samples (located as shown as A-D in Figure 5-2) were recovered during disassembly.

Resistance to water inflow was monitored in the same way for Test 8 as it was for all of the tests undertaken in this study. The results of this monitoring are presented in Figure A-13. Resistance to inflow gradually increased to a maximum of approximately 70 kPa by the end of three days of system operation. Resistance to influx was variable with considerable oscillation as water experienced opening and closing of flow paths as saturation and clay swelling occurred. At approximately 75 hours and then again at 85 hours there were sharp drops in flow resistance (almost to zero) with only partial recovery of the previously monitored flow resistance. After the second drop in flow resistance there is also a notable reduction in the degree of fluctuation in flow resistance within the system. These behaviours are due to two possible mechanisms, firstly the development of a preferential and semi-permanent flow channel through the system, or secondly as the result of an increasing degree of leakage from the cell due to problems in the water supply system.

A1.3 Tests having water inflow of 0.1 l/min

Eight of the 27 tests were operated at nominal water inflow rates defined as 0.1 l/min and for times ranging from 24 hours to 100 hours. Actual inflow rates varied from 0.08 to slightly more than 0.1 l/min but for discussion purposes, a rate of 0.1 l/min is assumed for all of these tests. One test (Test 4) was operated at an intentional total inflow rate of 0.09 l/min using three closely located inflow points. Tests operated at 0.1 l/min inflow are # 3, 4, 9, 11, 15, 17, 19 and 23. The duration that they operated ranged from 24 hours to 100 hours. The results of each of these tests are briefly described below.

A1.3.1 Tests 9, 11 and 15: 0.1 l/min for 24 hours

Tests 9 and 11 are replicate tests intended to establish the consistency of the water uptake behaviour of this geometry and inflow rate as well as to examine the effects of gaps that may or may not be present in the block assembly.

At 0.1 L/min the inflow into the tests is 6 l/hr which is close to the condition initially anticipated as being the limit between a system that is physically stable for a short-time (during ongoing back-filling operations) and one that will experience difficulty under conditions where there is only limited physical restraint provided by the backfill between the inflow point and the working face. Test 21 was conducted to provide comparative information on the effects of using crushed natural bentonite rather than manufactured pellets to fill the space between the block assembly and the surrounding "rock". All three tests were operated for only 24 hours in order to provide information on the short-term water uptake and movement characteristics of these systems.

Test 9: 0.1 l/min for 24 hours

Test 9 was constructed with 5-mm-wide gaps intentional left between block groupings (0.3-m-wide by 0.3-m-deep groupings) as shown in Figure A-15a. This simulated conditions where block sub-assemblies were installed but small gaps either remained between them or else the assemblies underwent slight shifting between placement and substantial water inflow. This test had 1,165.5 kg of blocks installed together with 462.5 kg of Cebogel pellet materials. Knowing the volume of the test and the volume occupied by the blocks it is possible to calculate the volume filled by the pellets. Taking this volume and the measured mass of pellets, the average dry density of the pellet-filled volume was calculated to be 1,140 kg/m^3.

Just prior to completion of the test, water was observed to be exiting the pellet and block assembly from the horizontal contacts between the pellets and blocks on the outermost stacks of blocks. Although exiting the test there was insufficient time between water arriving at the face and termination of the test for any fluid to reach the collection system or for material to be eroded from the test. This type of water flow along the block-pellet interface proved to be typical for most of the tests done in the course of this study. Test 9 had essentially no water uptake in the floor region below the blocks, and the uppermost pellet-filled volume was also still dry. There was also an apparently higher degree of block wetting along the intentionally vertical joints in this test, especially at the depth corresponding to the point of inflow. This indicates that water was moving along a changing phreatic surface from the inflow point and that the water was also moving through the pellets and into the block assembly (evidenced by very dark coloured blocks in Figure A-16). Water entering the blocks did not exit from the front face in the course of this test but in some locations had begun wetting the underlying pellets (Figure A-16).

The vertical joints intentionally built into Test 9 were measured during decommissioning and had undergone considerable closure, especially in the mid-depth region adjacent to the water inflow points (see depth 0.3-m in Figure A-16). This is attributed to mechanical pressures applied to the outside perimeter of the block assembly rather than swelling of the clay blocks although in the core regions this will also have contributed to system sealing. The dry block sub-assemblies at the front face of Test 9 originally had a 5-mm-wide gap but by the time of test dismantling these gaps had closed to less than 2-mm.

(a) Pre-Test Appearance (b) Initial Gaps (c) Closed Gaps

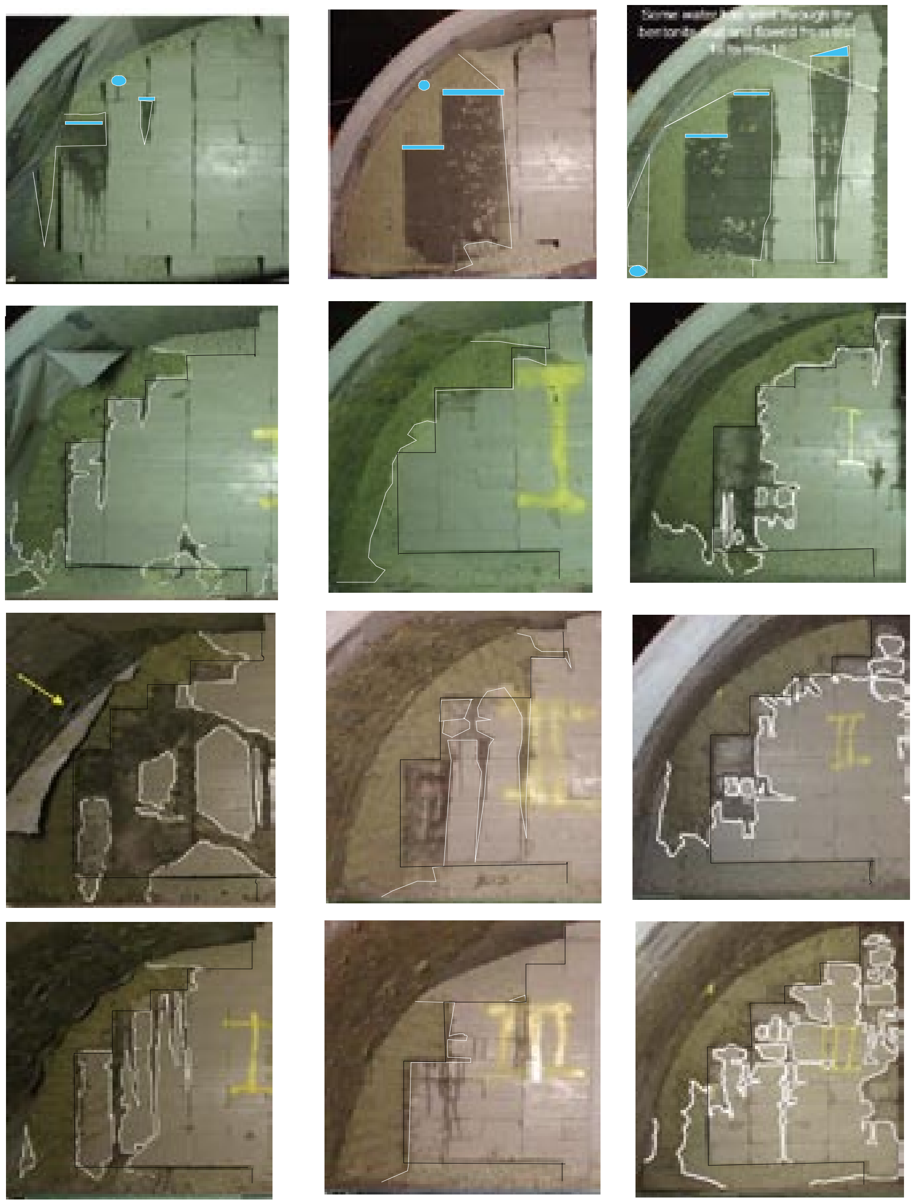
Figure A-15. Set-up of Test 9 and Test 10 (with 5 mm gaps installed).

Front Face

0.3 m Depth

0.6 m Depth

0.9 m Depth



Test 9 Test 11 Test 15

Figure A-16. *Water distribution in Tests 9, 11 and 15 (0.1 l/min for 24 hours).*

Test 9 experienced considerable water leakage at the point of connection between the water supply line and the concrete, making it difficult to evaluate the system behaviour after water leakage began at approximately 15 hours into the test. The inflow resistance readings remained constant after 15 hours of testing, a behaviour that was not observed in any other test done in this study and is attributed to the start of system leakage (Figure A-17). The normally observed behaviour for water inflow resistance is for early-stage oscillations in pressure as the water moves into the pellet and block assemblies with varying degree of resistance as water is alternately free-flowing through voids or encountering resistance as the pellets swell into the pore spaces. Prior to 15 hours there was also no evidence of water loss from the supply system and the water level within the test chamber had not experienced enough resistance to cause the inflow to backup and generate resistance to flow. Figure A-17 shows that there was an inflow resistance of no more than 20 kPa prior to the initiation of leakage that is very low and indicates that the system is taking water in as rapidly as it is being supplied. Up to 15 hours of operation the test had 90 l of water supplied to it representing 46 % of its total and 73% of its initially unsaturated air volume in the pellet-filled region.

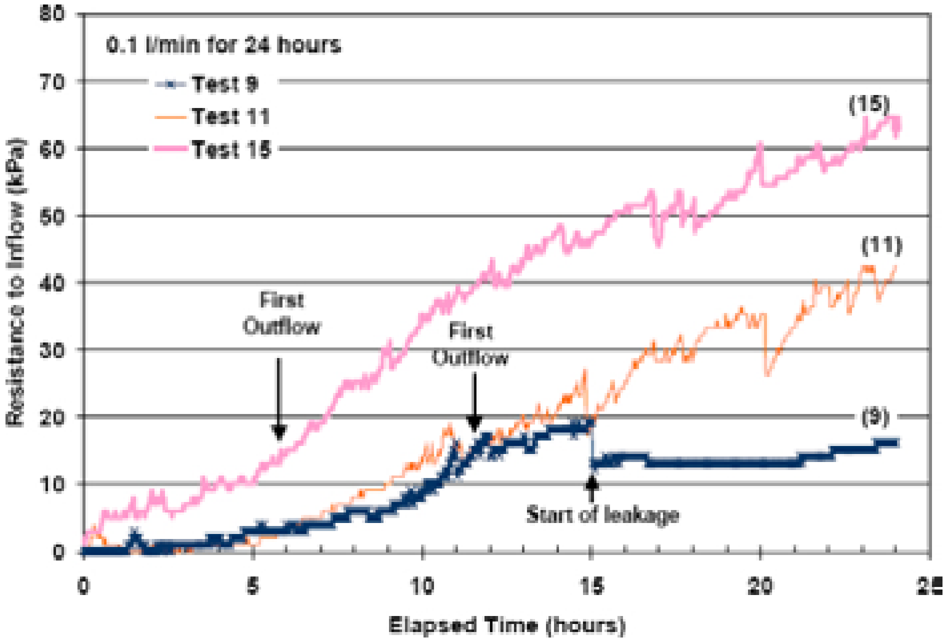


Figure A-17. Water inflow resistance in Tests 9, 11 and 15.

In order to gain information on the water content and density distribution patterns in the test at the time of its completion, several samples of pellet and block materials were recovered. The locations where these samples were recovered are shown in Figure 5-2 and the data is provided in Table A-5. These data support the visual observations regarding water distribution at the end of the test and indicate that the pellets closest to the water inlet have taken on the most water and have swelled, reducing the density of the pellet fill in that region. This may in part explain the very low resistance to inflow since lower density pellet-filled regions will have a very low swelling pressure. The vertical joints immediately adjacent to the water inlet appear to have to a limited degree acted as a pathway for water ingress into the core of the block assembly but this does not seem to have been an ongoing process. At the time of decommissioning these wetting paths did not seem to have recently seen water and were beginning to have their water adsorbed into the blocks themselves. Shortly after starting the test, the pellet materials above the blocks likely swelled sufficiently to block the small vertical pathways, redirecting the water forward along the block-pellet interfaces, as seen in Test 11 that was done without such gaps.

Test 11: 0.1 l/min for 24 hours

Test 11 was identical to Test 9; with the exception that there was a bentonite geotextile curtain was installed between adjacent test cells to prevent water crossing between test cells. Test 9 had previously established that water movement through the blocks was a secondary process of limited interest in terms of the 24-hour duration tests at water inflow rate of 0.1 L/min and Test 11 was the physical confirmation of that conclusion and was also constructed with these intentional gaps present. Test 11 contained 1,152.5 kg of Friedland clay blocks and 367.5 kg of Cebogel pellets in the 0.942 m^3 test chamber. The pellet-filled volume had an average dry density of 1,140 kg/m^3 and a macro void volume of 121.3 l. Water was supplied at a rate of 0.1 l/min via a single port mounted at mid-height of the test chamber and mid depth of the clay block-pellet assembly, at the pellet-concrete interface.

Test 11 operated as designed, with no leakage from the supply system and effective monitoring of inflow resistance and outflow rate being achieved. The test experienced first outflow 11.5 hours into the test (69 litres inflow). This represents 39% of the total and 49% of the initially present air void volume being filled with water before water outflow occurred. Water exited the test at various locations including the pellet-cell floor interface, the pellet-concrete interface and the pellet-block contacts. Water tended to exit as relatively clear fluid but on exiting the cell would often remove clay materials from the vertical face of the assembly. This is more of a downstream face erosive process than an internal erosion issue. The material removed was dominated by dark-coloured Friedland clay, as can be seen in Figure A-18 and shows the downstream face of Test 11 towards the end of its operation and shows how little material was actually removed by the exiting water in the course of this short test. Although no measurement was made of the mass of material removed in the course of the test there was not a substantial amount, given that only 56.4 litres of water exited the system, even if a very high erosion rate existed this volume of outflow would have had limited capacity to remove material. Observations made during testing indicate that material loss is likely in the order of 100–200 g.

Water inflow resistance measured for Test 11 was discernibly higher than for Test 9 (which may have had some system leakage not associated with flow through the test), although it still was not very high (Figure A-17). What is notable regarding the inflow resistance for both Tests 9 and 11 is the fluctuation in the inflow resistance. It would seem that the inflow rate is sufficiently rapid to either quickly hydrate a large proportion of the test making subsequent changes in flow patterns less substantial or else it has resulted in water flow being restricted to a more limited number of flow paths. The increasing flow resistance could then be attributed to the effects of slowly progressing overall system hydration (and swelling) that is trying to constrict the flow paths. The discrete flow path explanation is supported by the presence of persisting fluid flow along the various interfaces within the system.

This test was successful in continuously monitoring outflow from the system (excepting 2 hours) and the data is presented in Figure A-19. The outflow rate was very consistent for the entire test duration, averaging 0.084 l/min versus an inflow rate of 0.098 l/min. This means that the test has retained 84.5 l of the 140.9 l injected into it. This represents 43% and 61% of the total porosity and originally air-filled voids in the pellet-filled volume.

Water content measurements were made at materials recovered from several locations within this test as shown in Figure 5-2. The results are presented in Table A-5 and these, together with the visual observations show a system where water has moved into the pellet mass in the vicinity of the inflow port and then began to wet the adjacent pellet materials in a fairly uniform manner, with some preferential flow likely occurring along the concrete-pellet interface (wetting along wall to base of test). Early in the test there appears to have been preferential flow paths established that resulted in most of the water entering the system being transmitted rapidly out of the test rather than inducing much further wetting of the still dry regions.

Figure A-18. Eroded materials and water outflow from Test 11.

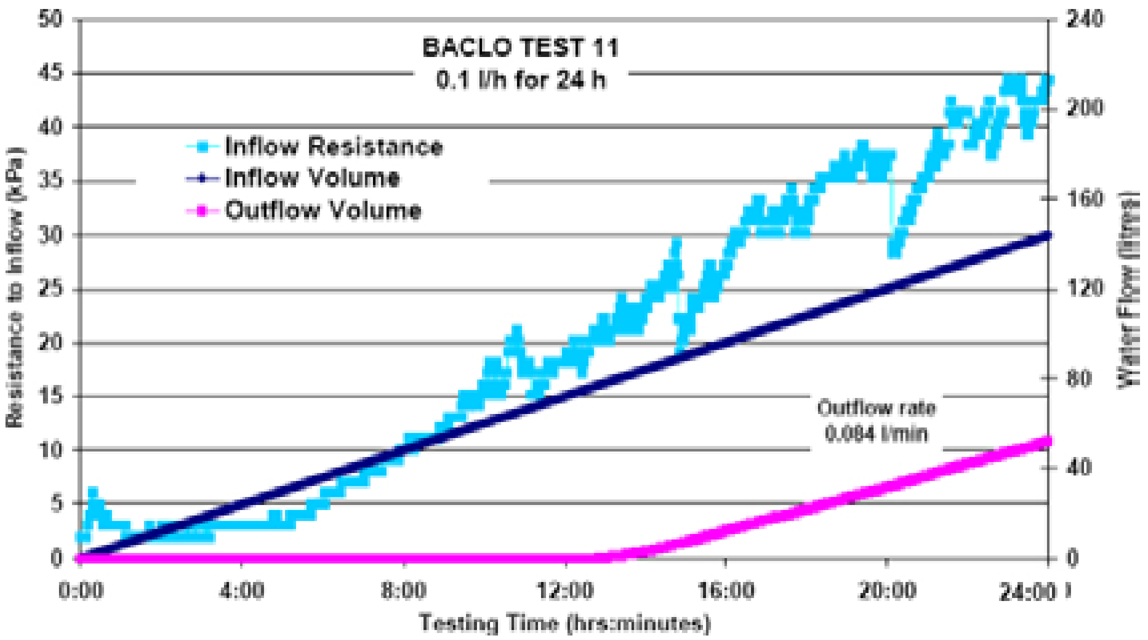


Figure A-19. *Inflow and outflow rates in Test 11.*

Table A-5. Water content of materials recovered from Tests 9, 11, and 15.

	Location*	Test 9 Cebogel (24 h) Water content (%)	Test 11 Cebogel (24h) Water content (%)	Test 15 Cebogel (24h) Water content (%)	Test 23 Minelco Floor (24h) Water content (%)
Pre-test	**Pellets**	**18.9**	**18.9**	**18.9**	**18.9**
Face	A	19	19	20	19
	B	19	81	32	19
	C	19	110	45	73
	D	19	19	19	25
0.3-m	A	64	57	61	19
	B	67	62	64	19
	C	49	58	19	67
	D	19	19	19	21
0.6-m	A	64	57	70	56
	B	82	54	75	63
	C	55	58	19	69
	D	19	19	19	42
0.9-m	A	67	19	71	58
	B	77	48	62	61
	C	43	56	43	65
	D	19	19	19	57

* As shown in Figure 5-2.

Test 15: 0.1 l/min for 24 hours

Test 15 was identical in construction to Test 11; there were 1,172.1 kg of Friedland clay blocks and 430 kg of Cebogel bentonite installed in this test. The pellet material had an average installed dry density of 1,070 kg/m^3 and a macro void volume of 133.4 l. Water was supplied at a measured rate of 5.85 litres/hour from a single location at mid height and mid distance into the test via a pipe that penetrated the concrete tube.

Test 15 operated as designed, with no leakage from the supply system and monitoring of inflow resistance, outflow rate and erosion were successfully accomplished. This test experienced first outflow only 6 hours into the test (as opposed to 11.5 hours for the pellet material examined in Test 11. This volume represents 18% of the total void volume and 27% of the originally air-filled void volume although some of the water was taken into the Friedland clay block materials water would have initially been almost entirely contained within the pellet materials. Water began exiting the test at two distinctly different locations, at the pellet-concrete-cell floor intersection and the lowermost horizontal contact between the block materials and the pellets (Figure A-20). The material removed by exiting water was dominated by the Friedland clay (a distinctly darker and more particulate material). Figure A-21 shows the downstream face of and sections at 0.3, 0.6 and 0.9-m distance from the front face. The water distribution in this short-term test indicates that water entered the volume closest to the inlet point and rapid swelling of the bentonite pellets occurred. Swelling resulted in the formation of a seal between the wetted volume and the more distant flooring materials and a dry pocket of material was able to persist under the block assembly. The inflowing water was gradually saturating the granular material in the upper regions of the assembly and was beginning to wet the Friedland clay blocks at the time the test was terminated.

Water inflow resistance measured for Test 15 was discernibly higher than for Test 9 although it still was not very high at the time of ending the test (Figure A-17). What is notable regarding the inflow resistance in Test 15 relative to Tests 9 and 11 is the lower degree of early fluctuation in the inflow resistance, (although some is still evident) and the higher rate of resistance development. It would seem that an inflow rate of 0.1 l/min is sufficiently rapid to either quickly hydrate a large proportion of the test making subsequent changes in flow patterns less substantial or else it has resulted in water flow being restricted to a more limited number of flow paths. The increasing flow resistance can be attributed to the effects of slowly progressing overall system

Figure A-20. Test 15 showing initial outflow locations (left) and outflow locations at time of test dismantling (right).

hydration (and swelling) that is trying to constrict the flow paths. The discrete flow path explanation is supported by the presence of persisting fluid flow along the various interfaces within the system observed in the course of the test as well as the short time required for water to exit the test. A total of 140 litres of water were injected into the test over a 24-hour period and only 3.8 litres exited, leaving 136 litres within the test. This together with the approximately 67 litres of water contained within the pellets totals 203 litres, the entire estimated porosity of this test (excluding that in the block-filled regions). As there were still considerable dry pellet filled regions then water must have been entering the clay blocks and joints between them. It should also be noted that there was considerable wetting of the downstream face of the test, as can be seen in Figure A-16, which accounts for several litres of the inflow, small variations in the dimensions of the test could also account for a considerable portion of the discrepancy between measured water uptake and observed degree of water saturation. This highlights some of the difficulty encountered in attempting detailed measurements in larger-scale tests.

Erosion of material from this test was very limited as there were only 3.8 litres of water that exited the test in its 24 hours of operation. The material removed was largely either clay dust from the pellet-filled region or Friedland clay that was removed from the downstream face of the test by the exiting water. Although not specifically measured, total erosion of material was certainly less than 50 g.

Test 15 was extensively sampled at the time of its dismantling, following the detailed sampling plan presented in Figure 5-2. The intensity of sampling allowed for the generation of water content profiles for the sampling depths of 0, 0.3, 0.6 and 0.9-m-depth within the test. These plots are provided in Figure A-21. These water content measurements show a system that has seen considerable water uptake in the upper and back part of the test. Water has clearly moved upwards into the crown regions in those areas resulting in very high water content conditions. This can be attributed to the looser, lower density pellet packing conditions near the crown of the test chamber. From the water inflow location, fluid has moved forward along the pellet-concrete interface and to a substantial amount moved inwards until reaching the pellet-block interface where it moved forward to the front face of the assembly. Much of the wetting at the front face shown in Figure A-21 can be attributed to water exiting the front of the test at the horizontal pellet-block interfaces and flowing down the face of the test, wetting the blocks and pellets. For comparison purposes, water content measurements taken at the same locations as in less intensively sampled tests are provided in Table A-5.

A1.3.2 Test 3, 4, 17 and 21: 0.1 l/min for 48 hours

Test 3 and Test 4 were the first assemblies installed with bentonite pellets between the block assembly and the inner wall of the concrete tube used to contain the experiment. Figure A-22a shows how the blocks of Test 3 (left) and Test 4 (right) were installed.

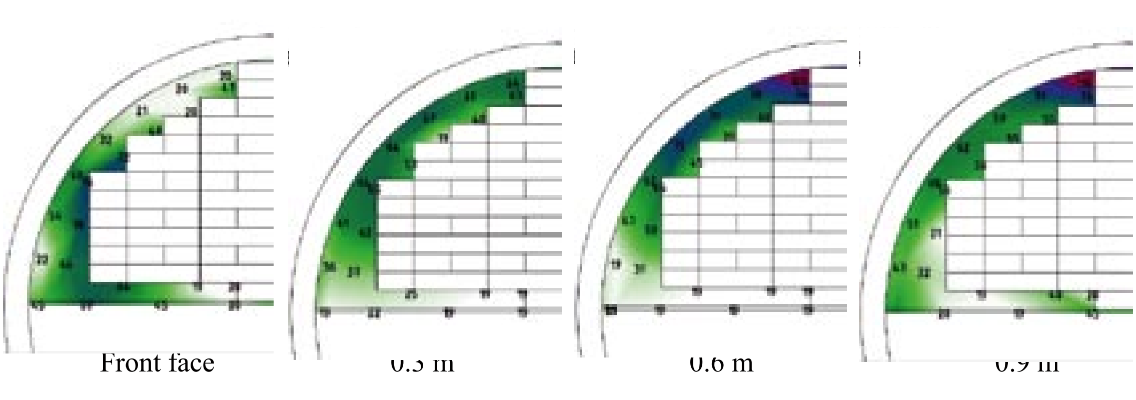


Figure A-21. Water content profiles for Test 15.

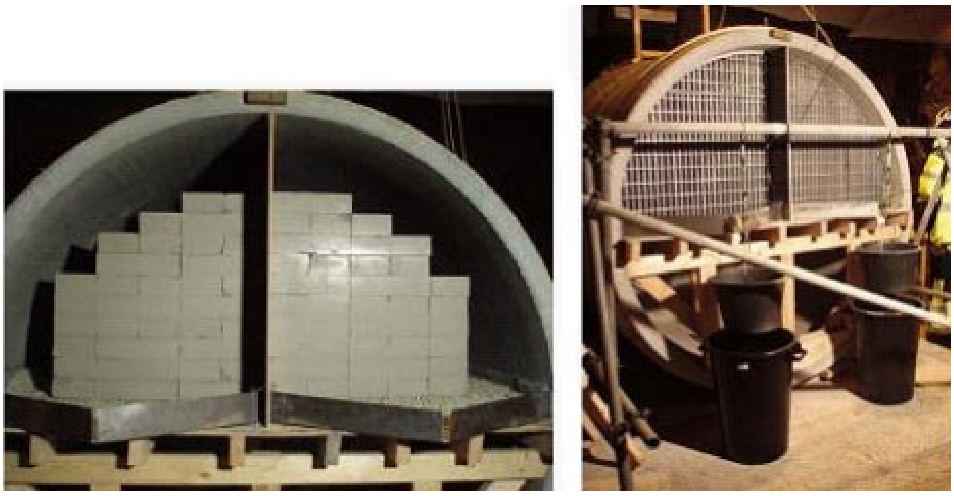


Figure A-22. *Test 3 and Test 4, prior to start of water inflow (note vertical divider installed to hydraulically separate left and right sides of test chamber).*

Being the first water influx tests conducted Tests 3 and 4 experienced technical difficulties that necessitated modification of the chamber for subsequent tests. The tests experienced leakage from the water supply system and unmonitored leakage from the rear of the cell once inflow water had reached that region (at about 24 h into tests). As a result time to outflow measured at the front face is of limited value since a second outflow location (rear of cell and leaking fittings), existed. Water outflow from the front of the cell first occurred between the unsealed contact between the plywood base-plate and back wall of the concrete tube and not flow into the buckets installed in the front of the chamber (Figure A-22b). Some water also exited the system via inadequately sealed water inlet connections in the concrete. The quantity of water lost from these locations was relatively small and clay loss was in the order of grams and so likely did not discernibly affect the overall results of these tests. However, in order to confirm the results obtained, Test 17 was installed and run.

The above-listed technical shortcomings were dealt with in subsequent tests through reconstruction of the restraint system, replacement of the plywood floor with a rigid steel plate and installation of a more robust mesh at the downstream face of the test chambers.

Test 3: 0.1 l/min for 48 hours

Test 3 had a single water inlet port and supplied the test with 0.1 L/min for a period of 48 hours. There were 1,126.6 kg of block material and 485 kg of pellets installed in this test.

As described above, Tests 3 and 4 experienced leakage from a number of locations by the time that 24 h of testing had occurred. This made measurements of time-to-water exit and inflow resistance problematic and the values obtained questionable. Despite these problems the water uptake patterns and inflow resistance measured proved instructive in the planning of subsequent tests. Test 3 began to show water outflow within minutes of Test 4 at 10.5 hours (63 litres water inflow), with two exit locations (shown with x's in Figure A-23). This volume represents 30% of the total porosity and 47% of the initially air-filled porosity of the pellet-filled volume. These outflow locations persisted for the entire test. Water inflow was constant at 0.1 l/min (6 l/h) for the entire test. The development of a leak in the rear of the test chamber resulted in loss of a portion of the inflow water via this pathway and so the data related to outflow rate or erosion are not entirely reliable. The resistance to inflow never exceeded 60 kPa, as can be seen in Figure A-24. Consistent water outflow to the buckets installed at the front of the tests began approximately 25 hours into the test. Initially the quantities of water exiting the tests were quite small but after approximately 4 hours of flow, the outflow became quite constant at ~2.5 l/h (versus 6 l/hr inflow). Subsequent overflow of the water collection buckets during the night resulted in a loss of outflow data until the next morning at which time an outflow rate of about 4.2 l/h was recorded (Figure A-25). At the time of dismantling, the difference between injected and exiting water volumes was approximately 1.8 litres per hour. Part of this volume was loss through leakage into the collection system associated with Test 4 (right-hand side of assembly). This makes the outflow plot provided as Figure A-25 of limited value since there is an unquantified secondary exit path for water. The remaining 4.8 litres per hour was moving directly through the test and being captured in the outflow collection system.

Dismantling progressed such that the test was taken apart as separate sections exposing the vertical face of the system at 0, 0.3, 0.6 and 0.9-m-depth (Figure A-27). After removing the first section to expose face "I", it could be seen that most of the pellets were wet with only a small pocket of dry material below the block assembly. Some water had entered the outer regions of the block assembly via the joints between the blocks (vertical and horizontal wetting patterns evident in Figure A-27). On reaching the second internal face (Section II in Figure A-27), dry pellets are again found in the base of the test as well as in the uppermost regions of the chamber. Water has entered a greater proportion of the block-filled volume, typically along joints; this may be associated with the proximity of this region to the water supply ports in the concrete tube (approximately 0.1 m distance from concrete to clay blocks). At the deepest section (III), the pellets are dry on the lower outermost portion of the test as well as under the blocks (Figure A-27).

Disassembly of Test 3 established that the pellet-filled portion of this test were largely water saturated within 48 hours of initiation of contact with a water source of 0.1 l/min but there is a distinct trend for the pellets underlying the blocks to remain dry and unaffected by the water entering (and exiting the system). The blocks were largely isolated from the water entering the pellet systems, tending to take water slowly into their matrix with some effect of joints between the blocks on the uptake pattern.

Physical dismantling of Test 3 included recovery of a limited number of physical samples of pellet and block materials to provide an indication of what the water content distribution and density was in the pellet-filled regions. Samples were recovered from the locations shown in Figure 5-2 and are water content values measured are presented in Table A-6. These data and the visual observations indicate a system where very thorough wetting has occurred in the rear of the test chamber and especially in the crown regions. The water has moved towards the downstream face but little has penetrated into the lower regions of the pellet fill, especially below the blocks.

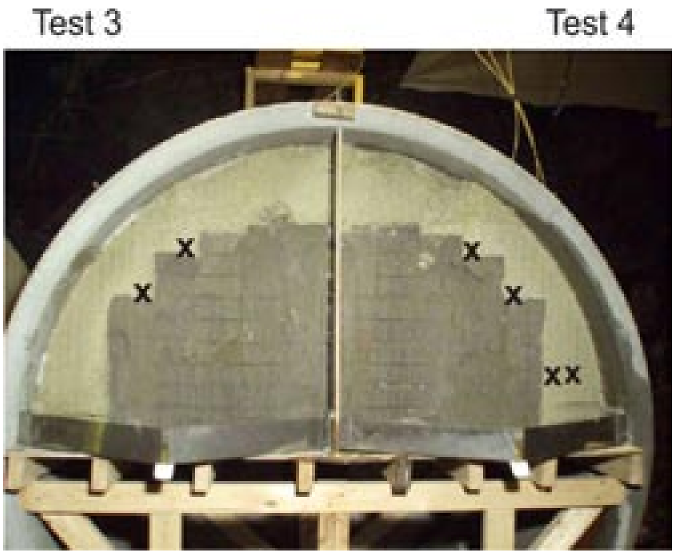


Figure A-23. Front face of Tests 3 and 4 at time of dismantling (x's mark location of outflow at time of test dismantling).

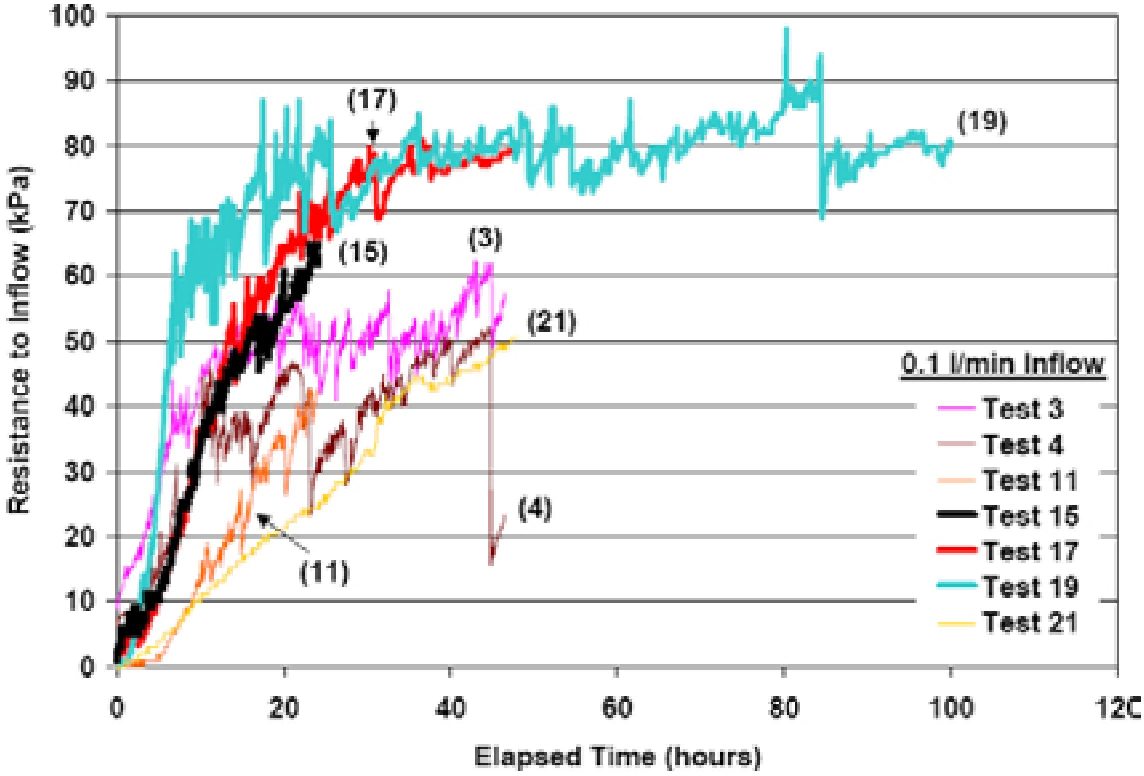


Figure A-24. *Resistance to 0.1 l/min water inflow for first 48 hours of testing.*

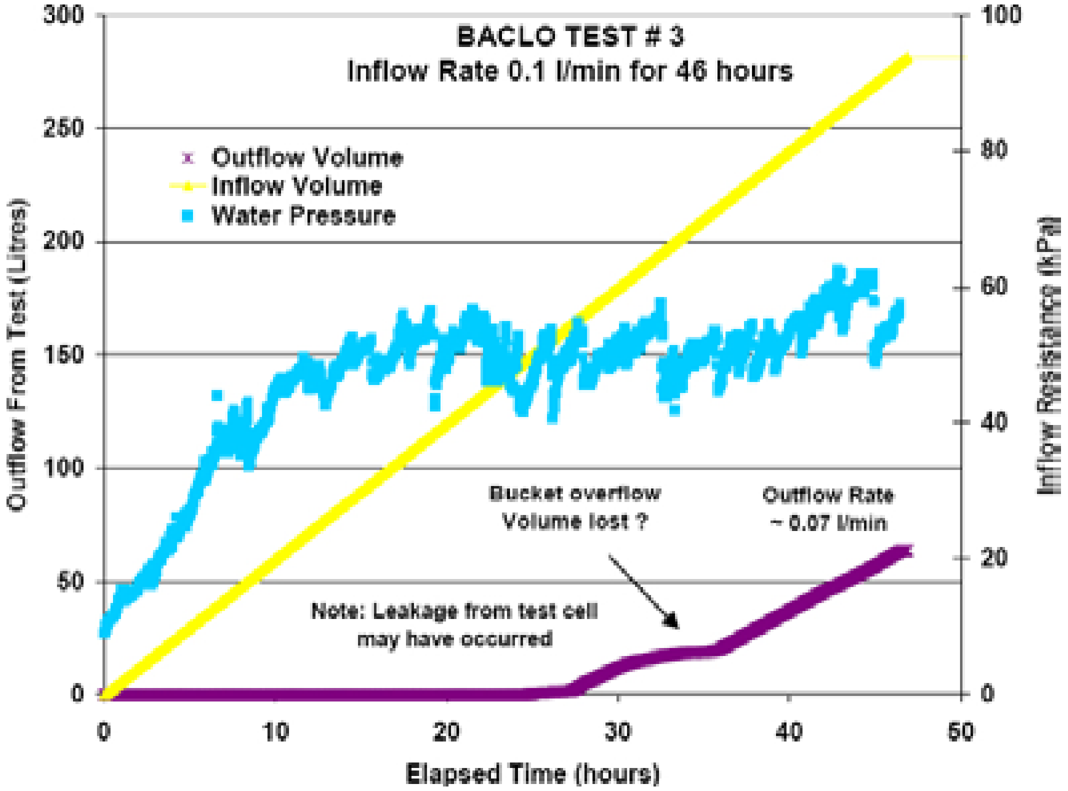


Figure A-25. *Inflow, outflow and flow resistance in Test 3.*

Table A-6. Water content of pellets recovered from Tests 3, 4, 17 and 21.

Depth	Location*	Test 3 Cebogel (48h) Water content %	Test 4 Cebogel (48h) Water content %	Test 17 Cebogel (48h) Water content %	Test 21 Minelco (48 h) Water content %	Test 19 Cebogel (100h) Water content %
Pre-test		**18.7**	**18.7**	**18.7**	**18.7**	**18.7**
Face	A	Wet**	Wet**	58	113	Wet**
	B	Wet**	55	45	78	Wet**
	C	76	Wet**	19	80	Wet**
	D	42	19	75	77	Wet**
0.3-m	A	Wet**	NM	61	76	Wet**
	B	Wet**	55	59	82	Wet**
	C	Wet**	NM	20	19	19
	D	19	19	20	21	19
0.6-m	A	Wet**	NM	62	67	Wet**
	B	101	76	78	82	Wet**
	C	19	NM	31	20	Wet**
	D	19	19	19	20	19
0.9-m	A	Wet**	NM	20	77	53
	B	Wet**	70	61	88	57
	C	19	NM	20	65	61
	D	19	19	20	22	25

* Locations shown in Figure 5-2

** Measurements not made but materials were much higher water content than at start of test

NM – sample to taken

Test 4: 3 x 0.03 l/min for 48 hours

Test 4 had three closely-spaced water supply pipes, each supplying water at 0.03 l/min installed midway along the concrete tube's length and at test mid-height. There were 1,126.6 kg of blocks and 485 kg of pellets installed in this test.

Water was first observed to be exiting from the face of Test 4 at 10.5 hours (63 litres water inflow), into operation but leakage had occurred from the back of the test chamber prior to this. The degree of saturation within the test at the time of first outflow was therefore somewhat lower than 30% of the total or 47% of the original air-filled porosity of the pellet filled region. Water outflow was initially measured to be 0.017 l/min and came from the pellets in the lower regions of the assembly but shortly after start of water outflow it also exited from the horizontal planes in the blocks assembly as shown in. Horizontal flow was largely associated with the block surfaces in contact with the pellet materials. Water exiting the test contained very little eroded material (although the quantity was not actually measured it was in the order of a few grams for the 48 hours of test operation). There may also have been material lost from the system as the result of the water that leaked from the rear of the test set-up although the quantity lost did not appear to be substantial (no accumulation on floor of tunnel). For the purposes of comparison with other tests, material lost can be estimated at approximately 100g.

At 26.5 hours into test operation, water outflow to the collection system was interrupted as the result of deformation of the plywood installed as a floor below the test assembly. As a result of this warping, water began to flow between the outflow channel and plywood plate to the room floor, bypassing the water collection and measurement system. This was complicated by the movement of some of the outflowing water in Test 3 into the collection system of Test 4 due to this deformation of the base of the cell. Outflow data for this test is therefore of limited value.

When water outflow measurement began it was estimated that about 1.5 l/hr (0.025 l/min) was exiting the face of Test 4 and by day 2 the outflow rate was approximately 4.3 l/hr (0.07 l/min). It should be noted that Test 4, like Test 3 had some water loss via the rear of the test chamber and so outflow rates recorded are lower than actually occurred. Water pressures in all three inflow pipes varied slightly (between 25 and 50 kPa) and cycled to some degree, generally not in unison. The trends of resistance to inflow development for each of the three inlet locations were very similar and so inflow resistance data for only one pipe (middle) is shown in Figure A-24 and Figure A-26. The fluctuation in the recorded inflow resistance may be a result of localized changes in flow resistance by the pellet and block assembly as the flow paths alter with evolving system hydration. There were two notable correlations between changes in inflow resistance and outflow. The first occurred at approximately 22 hours into the test when a drop in inflow resistance occurred, corresponding to the first consistent outflow from the test (Figure A-27). The second feature was at approximately 45 hours into the test when a sharp drop in the inflow resistance occurred (from 48 to 20 kPa). At that time there was a slight increase in the outflow rate of the system, shown by a slight steepening in the slope of the outflow plot (Figure A-27).

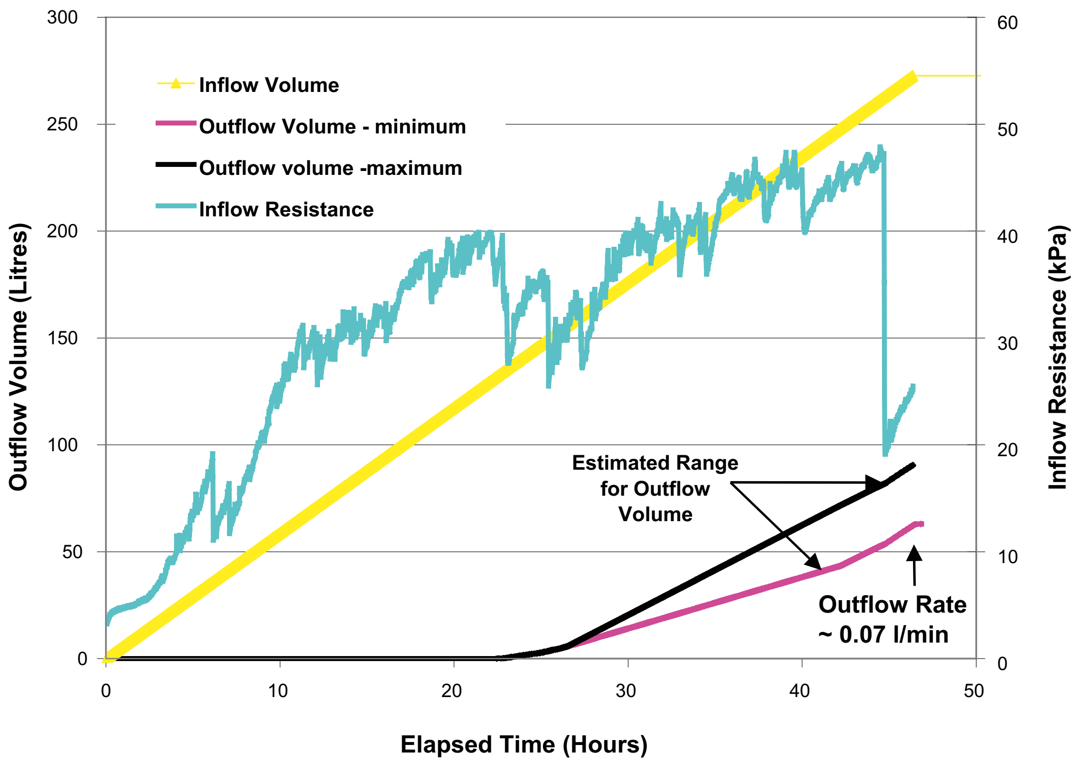


Figure A-26. Inflow and outflow from Test 4.

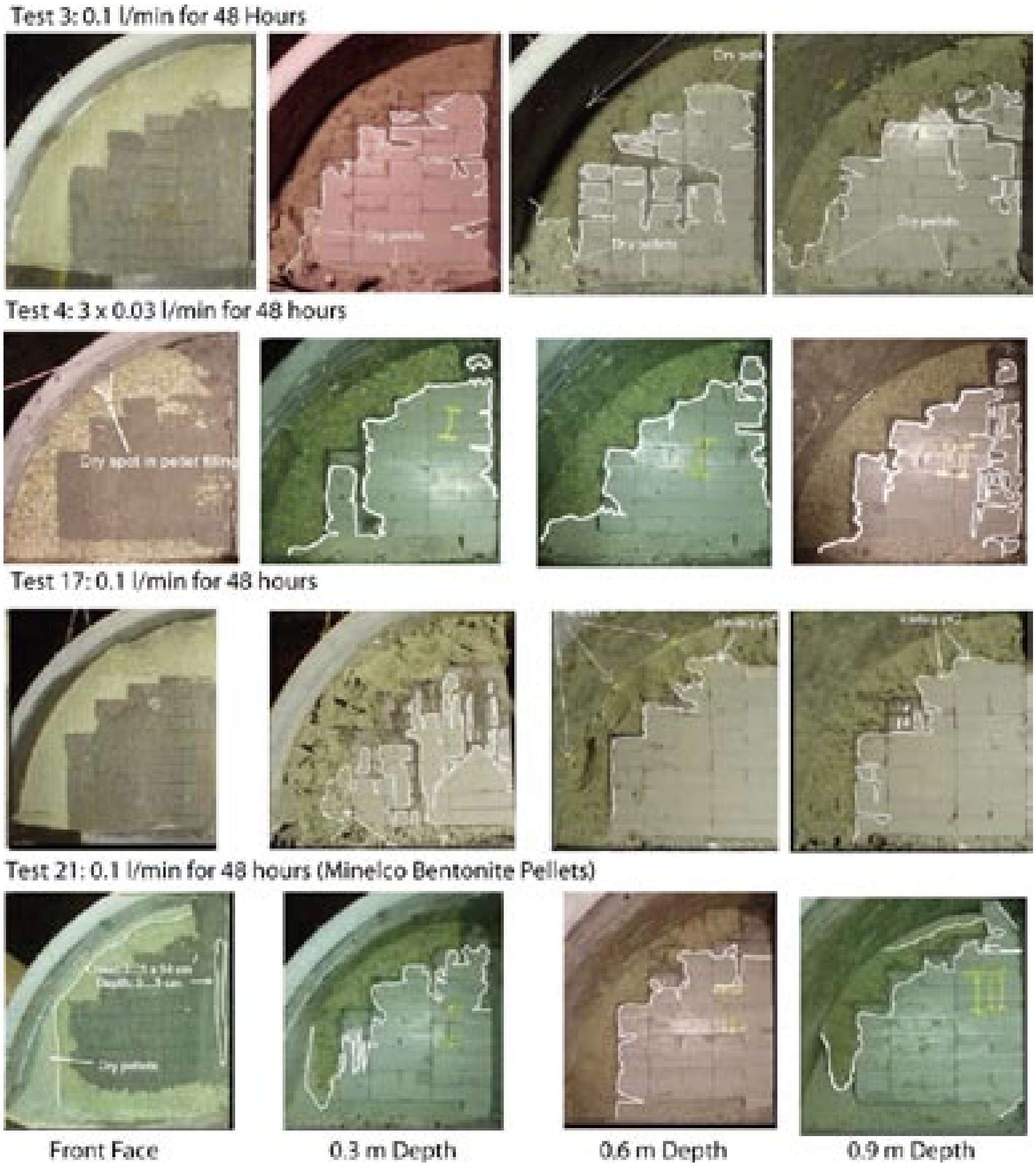
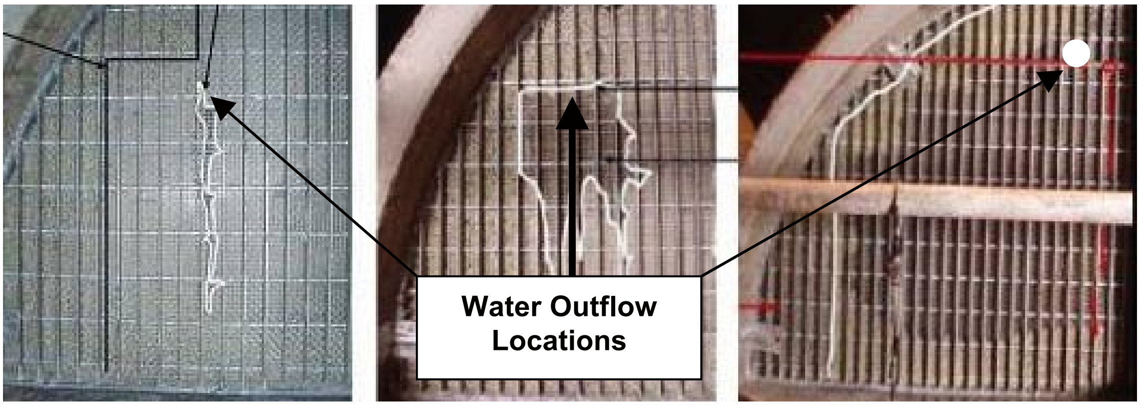


__Figure A-27.__ Wetting patterns for Tests 3, 4, 17 and 21 (0.1 l/min for 48 h).

Test 17: 0.08 l/min for 48 hours

Test 17 was constructed as a replicate of Test 3; which had experienced leakage and loss of outflow monitoring in the course of its operation. In this test there were 1,204.8 kg of Friedland clay blocks installed together with 415 kg of Cebogel pellet materials. Although the inflow to the system was targeted to be 0.1 l/min, only 0.082 l/min was actually supplied. This difference in inflow rate is not believed to be significant in terms of the overall system behaviour or evolution but has an influence on the calculation of inflow /outflow ratios and numerical assessments presented later in this document and for those assessments the actual, measured inflow rate is used.

Water began to exit the front face of Test 17 after approximately 2 hours and 50 minutes of test operation (13.9 litres inflow), via a vertical joint between the outermost blocks (Figure A-28a). This volume represented only 7% of the total void volume and 11% of the originally air-filled void volume. Outflow area then enlarged to include the horizontal contact between the pellets and the blocks as shown in Figure A-28b and then the flow path changed location and water began to exit from a small area towards the upper interior of the block assembly as shown in Figure A-28c. The pathway for water flow out of the test assembly was established within 24 hours and remained active until the termination of the test after 48 hours of operation. It would appear that the water found a discrete flow channel along the contact between the clay blocks and there was little evidence of self-sealing.



(a) 2h 50 min **(b) 7 hours** **(c) 24 hours**

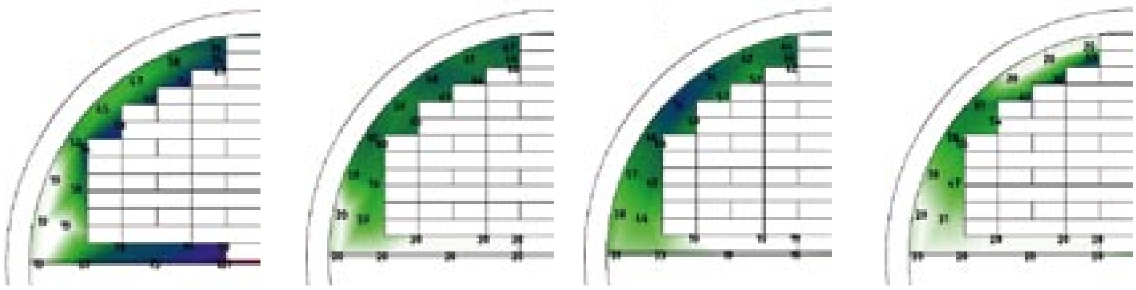
Figure A-28. *Changes in water outflow location in face of Test 17*

Test 17 also exhibited a different pattern of inflow resistance to that observed in Test 3 or Test 4. It had a relatively smooth and rapid development of its inflow resistance, as shown in Figure A-24. The inflow resistance was quite consistent with much less fluctuation that had been seen in previous tests at this inflow rate. The inflow resistance developed was somewhat higher than in Test 3 (80 kPa versus 60 kPa) and appears to have reached a plateau after approximately 24 hours of operation, the same time as a stable flow path was developed.

The movement of water through this discrete flow path induced considerable erosion in the Friedland clay blocks, much of it as the result of water flowing down the vertical face of the test assembly as it exits the system. Eroded materials were collected as part of capturing the exiting water and the mass of material removed was determined by oven drying of the collected material. In total 7.9 kg of material was estimated to have been removed in the 45 hours that outflow occurred. This quantity is based on small outflow samples taken over the course of the test and measurement of the clay within them. Test 17 had 235 litres of water injected into it in the course of its operation and 145 litres exited the system, leaving a total water uptake of 90 litres. This stored water represents 47% of the total and 72% of the originally air-filled volume in the pellet-filled region, although some of the water was also taken into the porespaces of the Friedland clay blocks.

Dismantling and sampling of Test 17 was undertaken at conclusion of 48 hours of water influx. The profiles present along the front face and at depths of 0.3, 0.6 and 0.9-m-depth are presented in Figure A-27. At the front face there was a considerable volume of pellet materials that had not yet been wet, largely along the perimeter and also under the clay block assembly. This pattern was maintained to a depth of 0.3 m with slightly more wetting in the pellet materials at the perimeter than was observed at the face while the basal region remained dry. At 0.6-m-depth (the same depth as the water inlet port), the pellets were fully wet with the exception of the base regions below the blocks. At 0.9-m-depth there was again the presence of a larger volume of dry pellets, including the crown region and along the lower perimeter of the assembly. The blocks showed little evidence of substantial water uptake excepting along the interface with the wet pellets where a thin wetting region was evident. The exception to this dry-block pattern is a thin band of wet block along the interface between blocks near the top of the assembly that connects with the location where water outflow occurred at the front face. The overall pattern of wetting here is strongly indicative of a narrow flow channel that moves horizontally across the test and then outwards towards the face of the block construction. The water does not seem to be flowing into other regions of the test to any substantial degree, beyond which it is drawn through the already wet regions by the suction of adjacent dry materials.

Test 17 was extensively sampled to determine the water content and dry density conditions within the test at the end of 48 hours. The results are presented in computer-generated contour plots for the test using the collected data (Figure A-29).



Front face 0.3 m 0.6 m 0.9 m

Figure A-29. *Water content distribution at the time of dismantling Test 17.*

The water content measurements show a test that has consistently high degree of wetting on the horizontal surfaces where pellets overlie the blocks and water flow was noted during testing (Figure A-28). These regions would have been in contact with water for the longest time and hence adsorbed more water than adjacent areas. Very high water content was evident in the volume of pellet material immediately adjacent to the inflow port and seems to occupy a relatively small portion of the total pellet volume, indicating that most flow was moving through that area to a contact with the clay blocks. The regions further from the inlet location (especially below the blocks at the floor of the test chamber were much less wet and in some cases the water content indicated no water had reached this area at all. The very high water content found at the base of the test at the downstream face can be attributed to the movement of water out of the test at the horizontal pellet-block interfaces and then flowing down the face of the test and entering the pellets at the downstream face, it is not the result of any preferential flow paths.

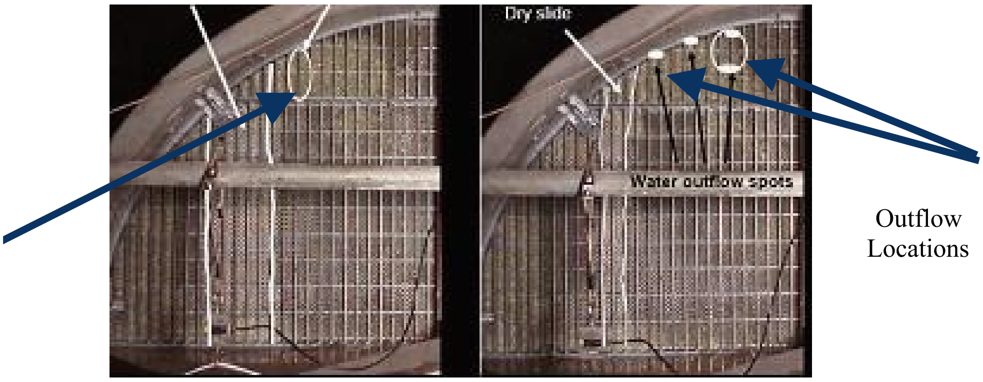
For general comparison to tests that were not so extensively sampled, data corresponding to the locations where samples were collected and are provided in Table A-6.

Test 21: Minelco granular bentonite 0.1 l/min for 48 hours

Test 21 was a repeat of Test 17 excepting that the Cebogel bentonite pellets were replaced by crushed granular bentonite (Minelco). There were 1,204.8 kg of Friedland clay blocks installed and they were underlain and surrounded by 390 kg of Minelco granular bentonite. As with Test 17, the inflow to the system was targeted to be 0.1 l/min but only 0.08 l/min was actually supplied to the test. This difference in inflow rate is not believed to be significant in terms of the overall system behaviour or evolution but has an influence on the calculation of inflow /outflow ratios and numerical assessments presented later in this document and for those assessments the actual, measured inflow rate is used.

Water began to exit this test sometime after 8 hours of operation and before 24 hours had elapsed (started during night). At 24 hours the test was exhibiting considerable water outflow at the horizontal interfaces between the blocks and clay granules at the uppermost layer of blocks. The location of outflow changed gradually between 24 and 30 hours with progressing hydration and self-sealing of the bentonite-filled volume. By 30 hours outflow was restricted to three points near the crown of the test at the pellet-concrete tube interface (Figure A-30). A total of 243 litres of water was supplied to the test during its operation and 110 litres exited, leaving 133 litres of water within the test. This represents 63% of the total and 96% of the original air-filled void volume within the pellet-filled volume in the test, but some of this retained water was also contained within the Friedland clay blocks. As with other tests it would appear that little water is actually being retained by the test at the time of test termination, most is being directed along discrete flow paths and out of the chamber (in Test 21 this was at the concrete-granule interface).

The resistance to water inflow for Test 21 was recorded and is presented in Figure A-24. It increased steadily for the 2 days of test operation and was still increasing at the time of test completion. It had only reached approximately 50 kPa during this time, a value very similar to



(a) 24 Hours (b) 30^{+} Hours

Figure A-30. *Changing water outflow locations in Test 21 (showing migration of outflow point(s) to concrete-pellet interface).*

Tests 3, 4 and 11. It would appear that the resistance to inflow of this material is very similar to other test installed and will not provide much in the way of short-term isolating capability to the backfill.

Water exiting the granule-concrete interface of Test 21 was clear and contained very little eroded material. The outflow was collected and dried to determine the quantity of solids removed in the course of the test. It is estimated that approximately 100 g of material was removed by the water exiting the test. This is much less than the 7.9 kg lost in Test 17 and in part reflects the flow path established (granule-concrete interface versus internal through Friedland Clay blocks).

Disassembly of Test 21 was conducted in the same manner as other inflow tests and the sectioning of the test exposed a wetting pattern than was similar to that observed for other tests conducted for the same duration and inflow rate. There was a tendency for the basal regions below the clay blocks to remain dry and the blocks themselves were only showing perimeter wetting for the most part. A limited amount of water penetration into some of the joints between the blocks was occurring but that had not progressed very far. The water movement into the block-filled central regions seems to have been largely prevented and the easiest pathway for the water entering the system once the pellet mass closest to the inflow point had hydrated was along the granule-concrete contact. Where wet, the granular bentonite did appear to have a more uniform degree of wetting and there was a clear preservation of the outline of the individual grains as can be seen in Figure A-31. This would be expected in a system where the highly adsorptive bentonite would tend to draw water into its matrix but where the elapsed time was insufficient for extensive homogenization to have developed.

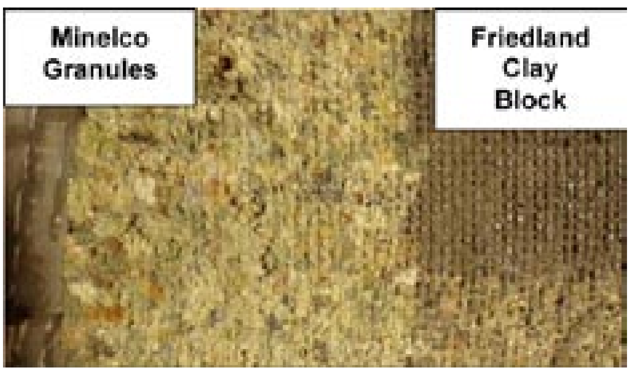
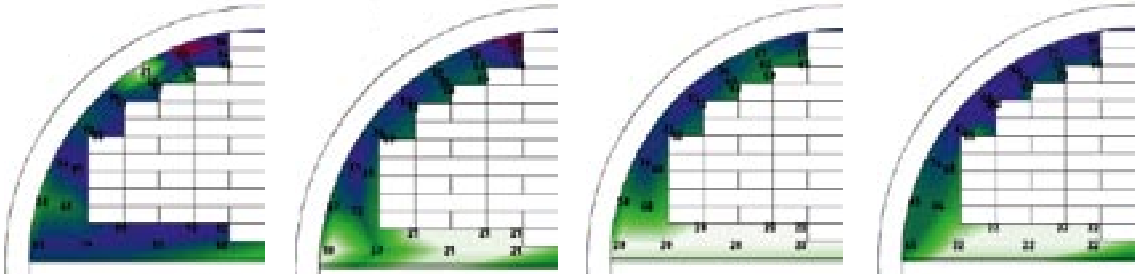


Figure A-31. *Appearance of granule-filled region at end-of-test (note partial breakdown of individual grains as swelling and homogenization begins).*



Front Face 0.3 m 0.6 m 0.9 m

Figure A-32. *Water content distribution in Test 21.*

Test 21 was extensively sampled as per Figure 5-2 allowing water content contours to be plotted (Figure A-32). For ease of comparison, samples recovered from the same locations as for other tests (Figure 5-2) where less extensive sampling occurred are presented in Table . The detailed water content determination shows a test that has taken on considerable water in the areas above the elevation of the water supply port. The water has clearly moved up into the crown regions for almost the entire length of the test but has not succeeded in moving into the basal pellets or blocks to a substantial degree. It would therefore appear that the Minelco pellets initially allowed for a more uniform wetting of the pellets but swelling sufficiently quickly sealing off the lower and core regions making the path of easiest water movement along the concrete-pellet interface.

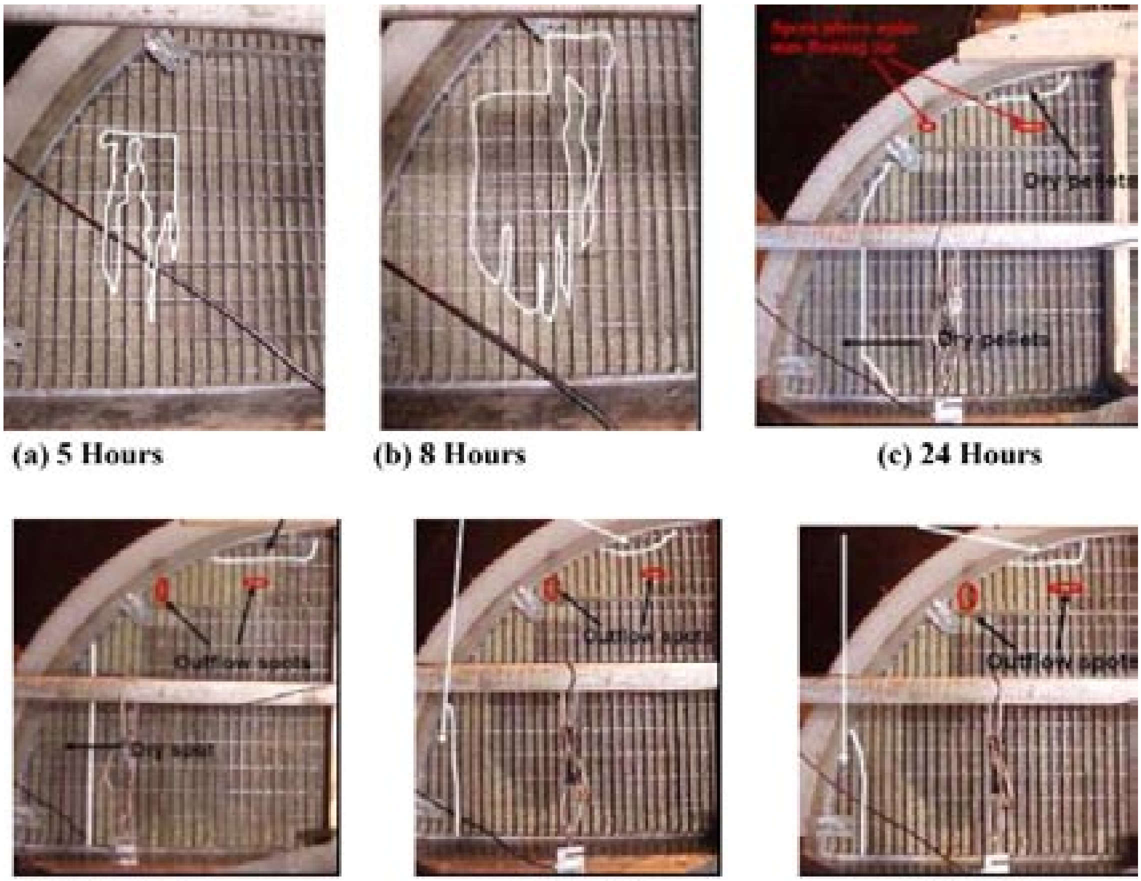
A1.3.3 Test 19: 0.1 l/min for 100 hours

Test 19 was the longest-running test conducted at a flow rate of 0.1 l/min in the course of this study. The test contained 1,204.8 kg of Friedland clay blocks and 410 kg of Cebogel pellets.

Water began to exit the front face of Test 19 after 4 hours and 55 minutes of test operation (29.5 litres inflow), via the horizontal contact between the clay blocks and the pellet materials at the same elevation as the water inlet (Figure A-33a). This volume represents 16% of the total and 25% of the originally air-filled pore volume in the pellet-filled region. Outflow area then enlarged to include more of the horizontal contact between the pellets and the blocks at the elevation of the inflow port, as shown in Figure A-33b. By the end of 24 hours of operation, outflow was established in two distinct locations, one at the concrete-pellet interface in the upper regions to the test cell and the other at the pellet-block interface near the top of the test assembly (Figure A-33c). Beyond 24 hours flow changed little (Figure A-33d-f), although the water exiting the block-pellet interface was eroding Friedland clay material from the front of the block assembly. At the end of the test 603 litres of water had been input and 244 litres had been retained in this test. The volume of water retained by the test is more than enough to fill the porespaces in the pellets and pellet-filled region even though that region was not completely saturated at the end of testing. The “excess” water volume can be attributed to the water retained by the Friedland clay blocks, especially at the downstream face of the test as well as wetting that occurred to the blocks close to the pellet-block contact (Figure A-35).

The resistance to water inflow to the chamber was recorded and is presented in Figure A-24 and is essentially the same as was observed in Tests 15 and 17. The resistance to inflow was variable with 10 kPa fluctuations evident for much of the test’s operation. An average resistance of approximately 80 kPa was established by the end of the first day of test operation, the same time as the establishment of the flow paths that persisted for the remaining 3 days of test operation.

There was discernible erosion in this test, largely associated with the flow channel in the upper region of the block-pellet assembly. Friedland clay material was clearly removed in the formation of this pipe and then further material was lost as the result of exiting water flowing



(a) 5 Hours (b) 8 Hours (c) 24 Hours

(d) 48 Hours (e) 72 Hours (f) 96 Hours

Figure A-33. *Evolution of water outflow locations in Test 19.*

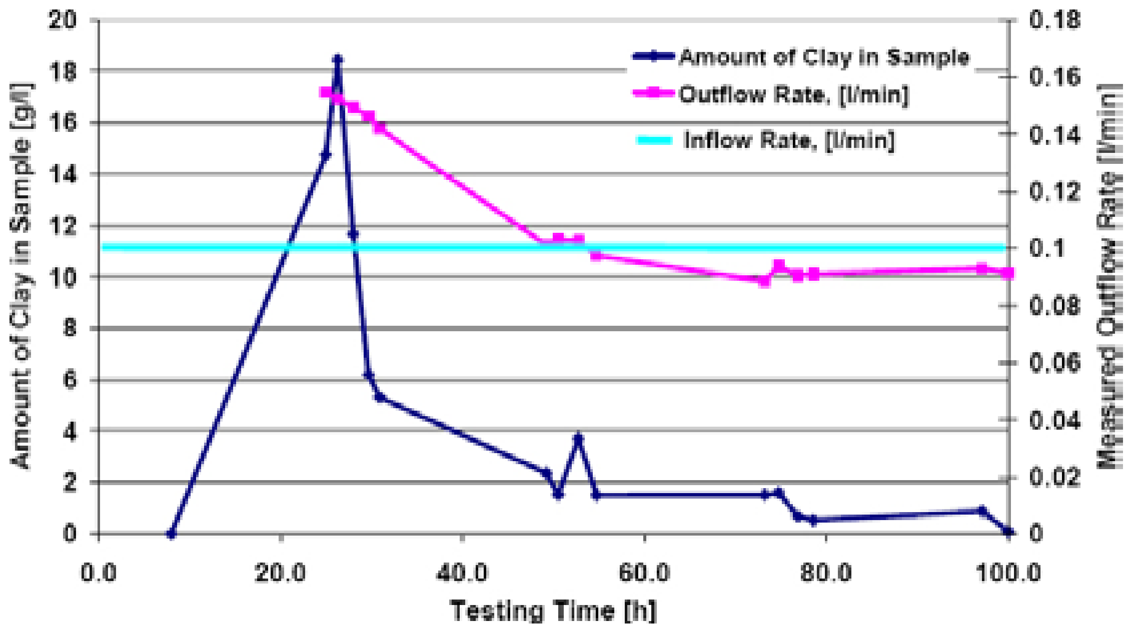


Figure A-34. *Erosion of clay from Test 19.*

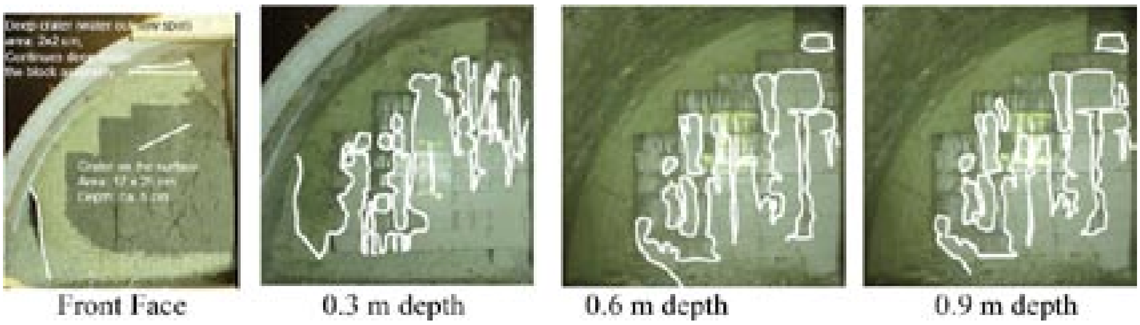


Figure A-35. *Wetting patterns in Test 19 (0.1 l/min for 100 hours).*

down the downstream, vertical face of the block assembly. The exiting water was captured and assessed to determine the quantity of material removed. Figure A-34 presents the erosion rate information developed and shows the typically observed high initial material loss followed very shortly with a much-decreased rate of material removal, associated with development of stable flow paths. Based on the collected sediment materials it was estimated that between 5 and 8 kg of clay was lost in the 100 hours of test operation.

Disassembly of Test 19 was done in the same manner as the other inflow tests done as part of this study with sections at 0.3, 0.6 and 0.9-m-depth, as shown in Figure A-35. On removal of the mesh at the downstream face of the test assembly, there were three features that were notable. The first two were small horizontal channels that extended into the block assembly near the upper portion of the test, corresponding to the right-hand side outflow point in Figure A-33. This outflow feature was associated with an eroded pocket of Friedland clay immediately below its exit point. The third feature, visible in both Figure A-33 and Figure A-35 was another erosion-related feature lower in the face of the block assembly where more Friedland block materials had been eroded in the course of testing. There was not visual indication of the flow path at the pellet-concrete interface and this location experienced very little obvious material removal in the course of the test. It would therefore appear that flow through this test has established itself along two low-resistance pathways, one at the test perimeter and the second internal to the system at the interface of the blocks and the pellets. Neither feature showed any tendency towards disappearing in the course of the test.

As the block assembly was taken apart there was a continuous zone of dry pellets present below the clay blocks, evidence that the water had not made its way through the pellets or blocks to the base of the test (Figure A-35). Wetting of the outside perimeter of the block assembly was relatively limited, although unlike most of the shorter-duration tests conducted at 0.1 l/min inflow, there was evidence of some water seepage along some of the vertical joints between the clay blocks as can be seen in Figure A-35. This seepage was not sufficient to fully saturate the block materials and showed no evidence of having reached the base of the test chamber.

Detailed sampling was undertaken in the course of dismantling this test, however, for the purposes of comparison with tests done with less-extensive sampling, data associated with sampling points A-D (Figure 5-2) are provided in Table A-6.

Test 23: Water inflow into base of test: 0.1 l/min for 24 hours

The tests done at 0.1 l/min inflow prior to Test 24 were done with the water supplied at chamber mid-height. In all these tests it was observed that there was a large volume of the pellets that remained dry, even after as much of 4 days of water influx. The effect of water supply from a lower elevation within the tunnel on the water distribution and movement within and through the tunnel was not addressed in the previous tests. Figure A-36 shows the location of the water inlets used in Tests 23 and 24. Installation of the floor to allow for basal wetting resulted in a slight reduction in the volume of the test cell and elimination of one of the rows of blocks installed in previous tests. This did not substantially alter the test layout and should not have influenced the water uptake and transport characteristics of these tests.

Test 23 contained 1,073.9 kg of Friedland clay blocks and 455 kg Cebogel bentonite pellets. Water was supplied to the base of the test at a rate of 0.1 l/min for a period of 24 hours. Water uptake by and exit from the test was monitored for the entire duration of the test. At the completion of the test it was disassembled and sampled to determine water distribution patterns. Wetting was noted at the front face of the test after only 2 hours of operation (12 litres total water supplied) and was exiting the system along the floor-pellet interface. This represents 6% of the total and 9% of the originally air-filled porosity of the pellet-filled region. Seepage via this location was initially slow (0.2 l in first 5 hours of seepage) and it was not until some time after 7 hours into the test that seepage became localized enough to pinpoint its location. During the early wetting water uptake at the downstream face seemed to be largely limited to a thin layer of pellet material close to the floor. Between 7 hours and 24 hours the system underwent considerable change in its outflow and wetting characteristics as can be seen in Figure A-37. The clay pellets surrounding the water entry point had hydrated and were providing enough resistance to water movement that resistance to water inflow was less in the vertical direction, resulting water moving upwards into the dry pellets surrounding the test. At some point water established a semi-permanent flow path, either along the contact between the clay blocks and pellets or perhaps between the vertically-aligned blocks located adjacent to the water inlet (see very wet section of blocks above inlet point in Figure A-38). Based on the change in resistance to inflow shown in Figure A-39 it would appear that this permanent flowpath developed at approximately 7 hours into the test, when resistance started to decrease. With flowpath establishment, water continued to exit near the crown of the test assembly, as can be seen in Figure A-37.

Disassembly of Test 23 was conducted in the same way as all previous tests with the vertical face exposed at distances of 0.3, 0.6 and 0.9-m distance from the original front. Figure A-38 presents the wetting patterns observed for the test. Despite the water being supplied to the base of the test, there were still considerable volumes of dry pellets present within the test at the end of 24 hours. Water seemed to have moved upwards into the assembly at approximately the location of the water source and also followed the clay pellet – clay block interface for much of the duration of wetting. Volumes of pellets were still dry adjacent to their contact with the concrete tube, indicative of a slower wetting process, likely driven by suction rather than advective forces. The clay block assembly showed extensive wetting in its lower region at 0.9-m depth and especially at 0.6-m distance (water inlet depth), from the front. Water had shown little penetration into the block assembly at 0.3-m depth or the front face although water was moving along the upper horizontal surfaces marking the clay pellet – clay block interface. The front face of the test was very wet on its right-hand side, this is largely associated with surface wetting as the result of water exiting from the upper portions of the test and then running down the vertical face. This water exiting the test induced considerable surface erosion in the Friedland clay block materials and was the cause of most of the erosive action observed.

Test 23 experienced very substantial fluctuations in the resistance it provided to inflow, particularly after about 7 hours of operation (observed first outflow from upper portions of block assembly). The 42 litres of inflow in the first 7 hours of operation represents 20% of the total and 33% of air-filled void volume in the pellets although not much of the water apparently moved into the pellets at the time of first outflow. The resistance varied as much as 40 kPa with many sudden increases and decreases with no discernible pattern (Figure A-39). This can be attributed to water being forced to change its flow path as the blocks and pellet materials clogged and broke loose within the relatively small flow paths being developed by the system. Ultimately at the end of the 24-hour test resistance to flow was averaging 60 kPa. This is approximately the same value as was observed for the other tests installed and run at 0.1 l/min inflow. In total 138 litres of water were injected into this test with only 17 litres exiting, leaving 121 litres in the test. This volume represents 58% of total and 88% of the originally air-filled pore volume of the pellets.

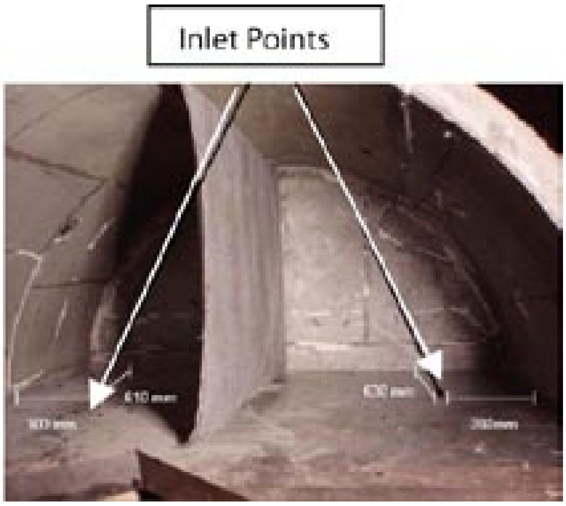


__Figure A-36.__ Water supply to base of Tests 23, 24, 27, 28.

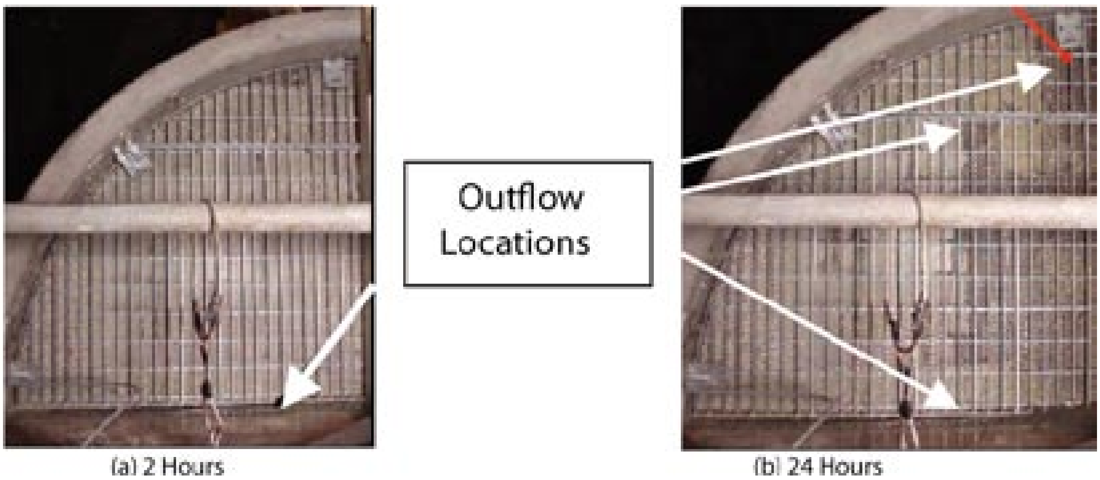


Figure A-37. *Water outflow locations in Test 23. (Water outflow locations migrated vertically with time and increasing degree of saturation).*

There was some loss clay from Test 23 as the result of water flow from the block assembly. In total 0.425 kg of material was collected during the 24-hour-long test. Most of this was Friedland Clay Block material, eroded as the water flowed down the face of the block assembly after exiting the test. There was a minor amount (a few grams) of bentonite clay removed early in the test as the water first exited at the floor – pellet interface. The eroded material was predominantly dust that was carried out by the water before it could swell sufficiently to resist removal. Some of the 425 grams of eroded material was clearly from the interior of the test assembly as there was the open flow channel that exited the test near its crown. It would not appear that this was an active short-term erosive environment given how little material was removed.

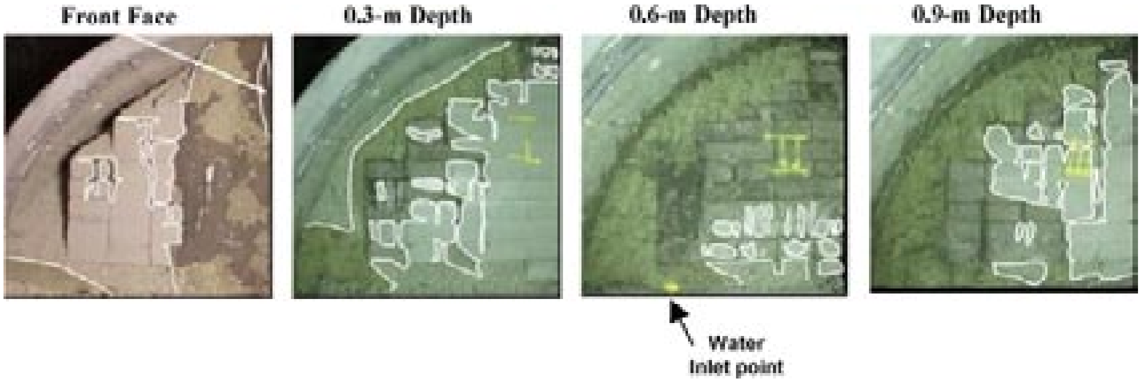


__Figure A-38.__ Wetting patterns for Test 23. (Extensive wetting in rear portions of assembly, including water movement into joints between blocks. Front and basal regions have less complete wetting).

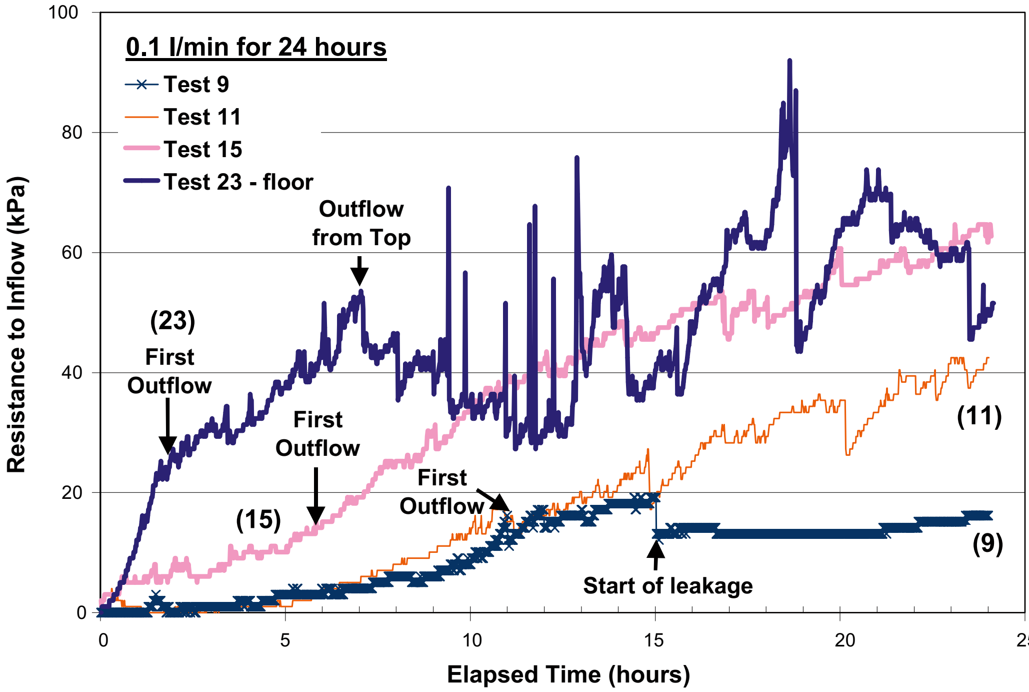
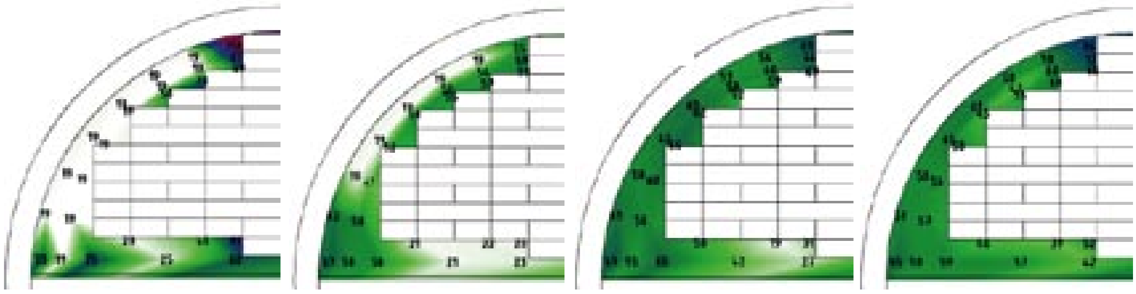


__Figure A-39.__ Inflow resistance of Tests 9, 11, 15 and 23.

Detailed sampling of this test was done as part of the dismantling process and the water contents determined for the sampling faces in the test are presented in Figure A-40. For the purposes of comparison with tests done with less extensive water content sampling data associated with sampling points A-D (Figure 5-2) are provided in Table A-5. The detailed water content measurements show a test where the water entering from the floor has first flooded the rear of the test cell and has perhaps moved along the floor level at the outer corner of the cell. Water seems to have moved preferentially towards the top of the cell where pellet density is lowest and resistance to inflow is least and then flowed forward along the horizontal block-pellet interfaces. How water moved from the floor to the crown regions is uncertain and would appear to have been via interface flow along the concrete-pellet contact on the left side of the cell at the mid-distance of the test (where inflow points located).



Front 0.3 m 0.6 m 0.9m

__Figure A-40.__ Water content contours for Test 23.

A1.4 Tests having water inflow of 0.25 l/min

Ten of the 27 tests done in the course of this study were operated at a water inflow rate of 0.25 l/min for periods ranging from 5 hours to 100 hours. Tests operated at 0.25 l/min inflow are # 6, 10, 12, 14, 16, 18, 22, 27, 28, 29. As with the tests conducted at 0.1 l/min inflow they had their resistance to water influx monitored, their wetting patterns recorded, erosion quantities, inflow/outflow ratios and water content distributions measured. Water was supplied to these tests in exactly the same perimeter location as was used for tests done at other inflow rates.

A1.4.1 Tests 6, 10, 12 and 14: 0.25 l/min for 5 hours

Test 6: 0.25 l/min for 5 hours

Test 6 was the first test conducted at an inflow rate of 0.25 l/min and is intended to provide an indication of how rapidly water could exit a section of backfilled tunnel where operations had ceased for a brief period. This test contained 1,169.5 kg of Friedland Clay Blocks and 475 kg of Cebogel pellets installed as shown in Figure 3-2.

Water became visible at the downstream face of Test 6 after 2 hours of operation (30 litres of water inflow). This volume represents 16% of the total and 26% of the original air-filled porosity of the pellet-filled region. This outflow occurred at the right-most horizontal pellet – block interface (closest to elevation of the inflow port). At 3 hours the pellet-block interface at the next – highest elevation within the test began to produce water. The quantity of water that exited the test was not substantial with only approximately 0.75 l of the 75 l input managing to exit the test during the 5 hours of its operation. The volume retained represents 39% of the total and 65% of the original air-filled pore volume in the pellet-filled region. The small quantity of water exiting the test flowed at approximately 0.03 l/min or 12% of the inflow rate. It is anticipated that the proportion of water exiting the system will increase with time as its degree of saturation increased and flow paths were established. Figure A-41 presents the wetting patterns present at the time of test completion.

Disassembly of Test 6 was done as per all the tests in this study with characteristics of the vertical faces at 0.3, 0.6 and 0.9-m-distance recorded and sampled. Water had apparently moved to the rear of the assembly initially (note high degree of wetting at 0.9-m-depth), until it reached a degree of filling sufficiently to induce flow towards the front. The inflow rate was sufficiently high to overcome some of the difficulties it had entering the joints between the blocks that had been observed at 0.1 l/min. There was considerable water entry into the block joints although no outflow was occurring from joints in the short time this test operated. Sufficient self-sealing had occurred in the short duration of this test to have induced a dry pocket of pellets below most of the block assembly and the pellet volume closest to the crown of the test was still dry.

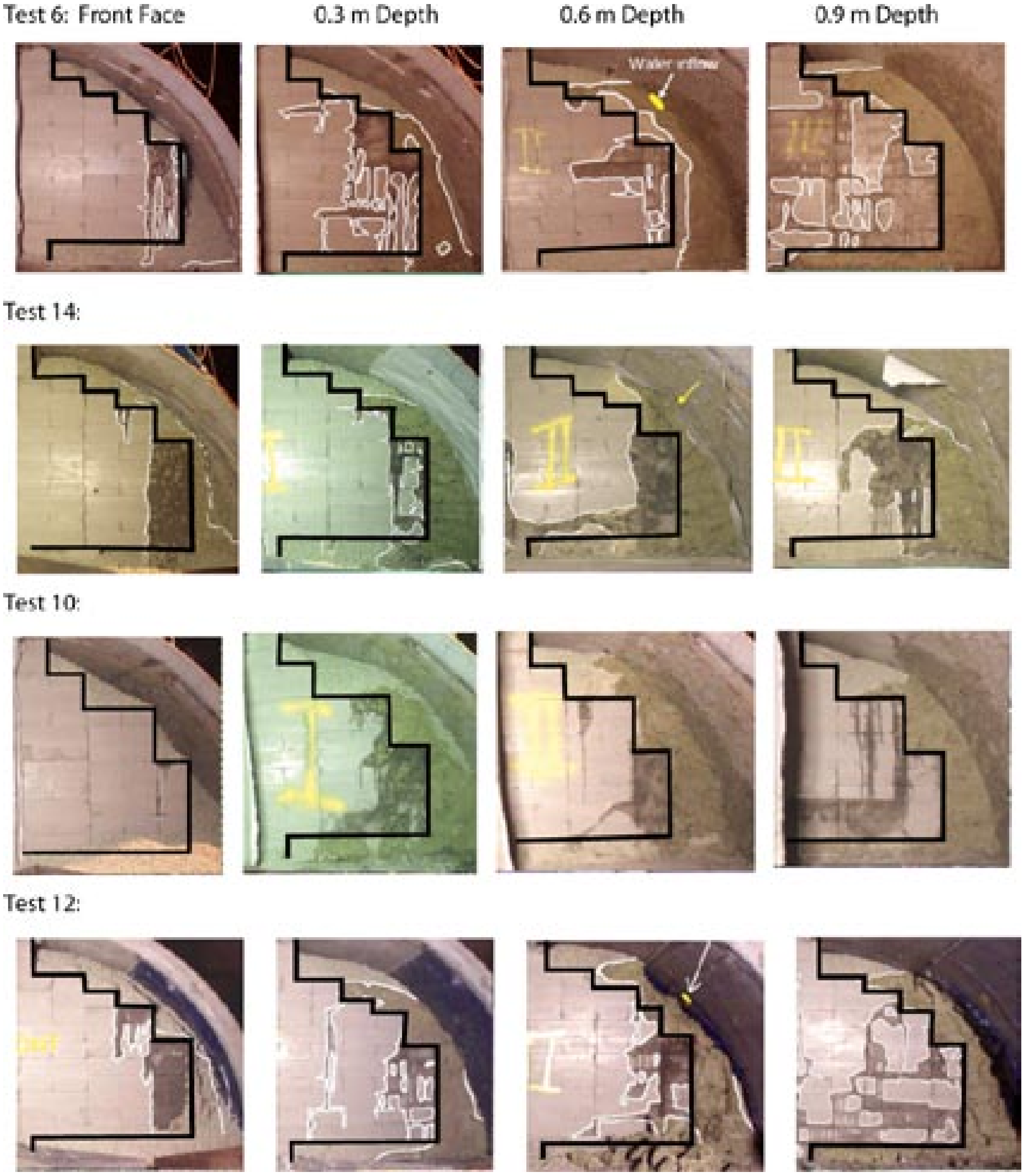


__Figure A-41.__ Wetting patterns in Tests 6, 14, 10 and 12 (0.25 l/min for 5 h)

Resistance to water inflow was measured for the entire duration of this test and is presented in Figure A-42. There is very limited resistance to inflow developed over 5 hours of testing with only 22 kPa developing. The degree of resistance to inflow was gradually increasing and showed very little fluctuation, indicative of a system that has either developed a discrete and stable flow path or else has yet to encounter any substantial resistance to flow (e.g. sand or gravel). Given the short duration of this test the second explanation is most likely.

There was essentially no outflow from the system and as a result no measurable erosive activity. This test therefore provides a starting point to allow definition of the limiting time for backfilling operations that would avoid erosion at this flow rate.

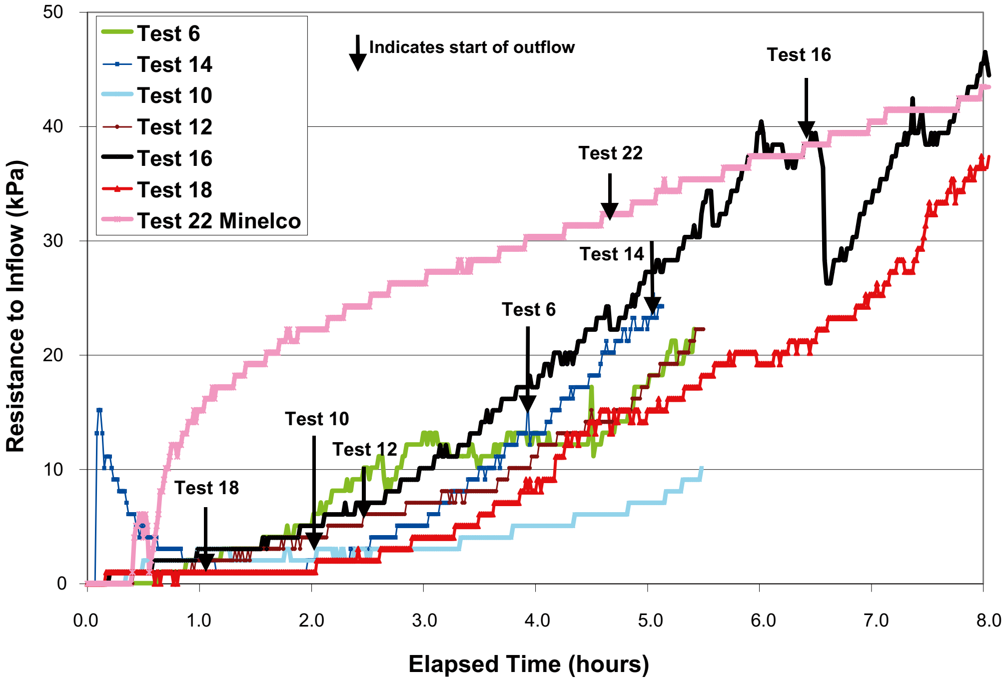


Figure A-42. *Resistance to water inflow for first 8 hours of testing.*

As the testing time was very short, there was very little time for the system to take on and internally distribute the water entering the system. As a result of the limited water distribution only sparse sampling of those regions where water uptake was evident was done during dismantling (shown in Figure 5-2 as locations A-D). The results are presented in Table A-6. These results together with the visual observations show a system where water moved rapidly from its injection location into the pellet mass. Once the water encountering the low-porosity, relatively impermeable clay blocks, it moved along the pellet-block interface, either wetting adjacent pellet materials or else exiting the front face of the test.

Test 14: 0.25 l/min for 5 hours

Test 14 is a replicate of Test 6 with a block-pellet assembly provided with 0.25 l/min of water via a single perimeter port located at mid-height and mid-depth. There were 1,204.8 kg of Friedland clay blocks and 405 kg of Cebegel pellets installed. The test operated for slightly more than 5 hours.

Water was observed to be exiting the test at about 5 hours (75 litres inflow) into the test, exiting from the base of the test where the floor, concrete wall and pellets meet. Small amounts of water were also observed to be exiting from the lowermost horizontal contact between the clay blocks and clay pellets (Figure A-43). This volume represents 40% of the total and 60% of the air-filled void volume in the pellet-filled region and although some of the water would have entered the Friedland clay block materials most would be associated with the pellets. There was no measurable outflow from the system before the test was ended (water had just begun exiting the test when the testing time had expired). The outflow locations were identical to those observed for Test 6, excepting that Test 6 required only 2 hours for water to reach the downstream face of the test. There was also a very limited quantity of outflow in Test 6 (0.75 l of the 75 litres injected), which is essentially the same as was observed for Test 14 (~nil in 5 h). The patterns of water distribution are similar for Tests 6 and 14, with only minor variations in where water entered the pellet-fill. This indicates that there is at least a limited degree of predictability about where water will move in a pellet-block assembly during the initial hours following their installation. The tests indicate that there is only a limited time available (2–5 hours), for backfilling operations to proceed beyond 0.6-m from the water inflow point before it begins to exit the already installed materials, at which time it could affect ongoing operations.

__Figure A-43.__ Test 14 at 5 hours, showing where water outflow was observed.

Resistance to water inflow was monitored for Test 14 and is presented in Figure A-44. The maximum inflow resistance at the pellet-inlet contact was in the order of 24 kPa, essentially identical to that observed in Test 6. Once again this indicates a system where very little resistance to water influx is present and water is entering essentially unhindered.

Test 14 was extensively sampled to determine the water content distribution within the block-pellet assembly than tests done prior to it. Figure A-45 presents a computer-generated contour plot of the water content and density information collected during dismantling. These data indicate that there is a volume of clay pellets adjacent to the inflow port that are hydrated and that water had initially moved preferentially towards the back of the cell, saturating that region before flow began to move forward. Wetting seems to have been greatest in the contact between the pellets and the upper, horizontal surfaces of the clay blocks with water moving forward along this contact toward the face of the test.

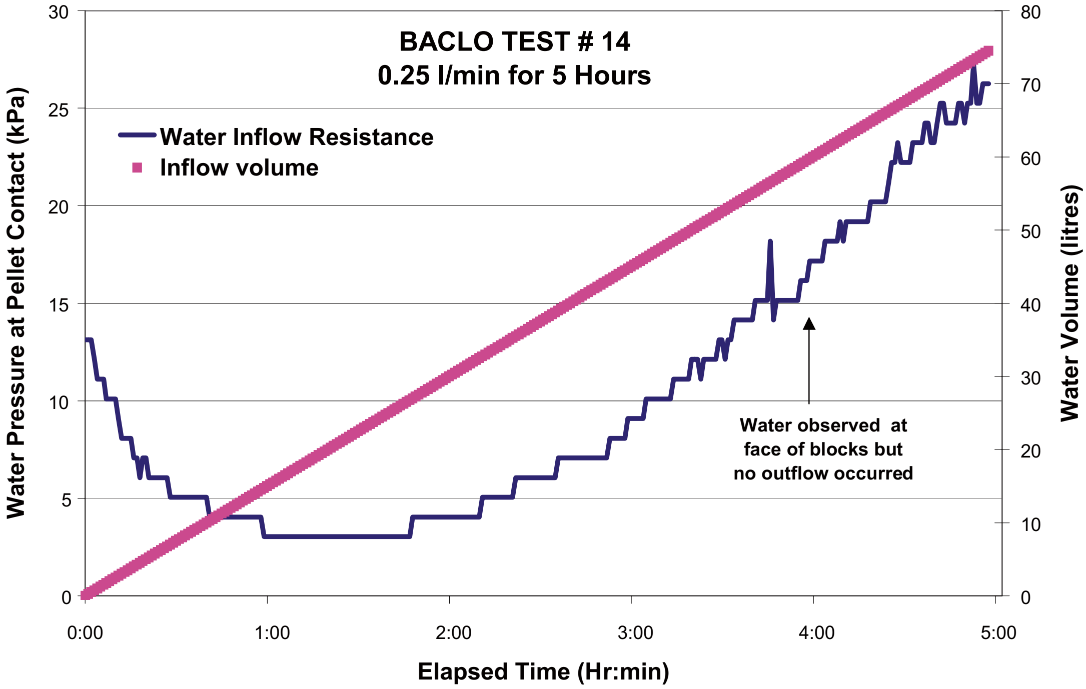
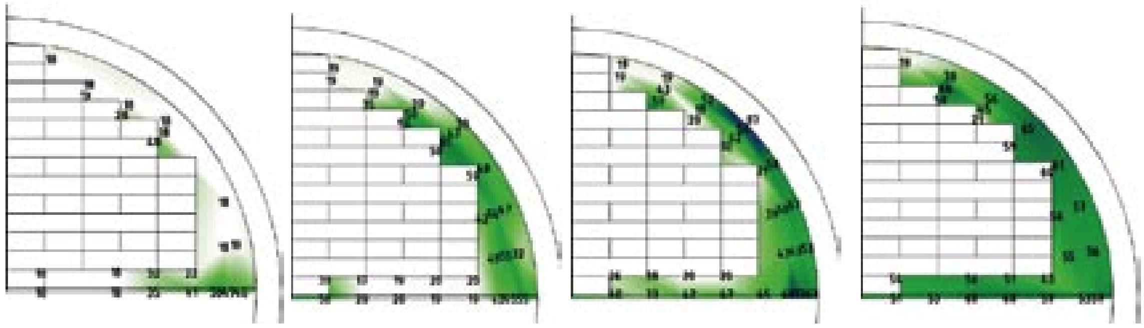


__Figure A-44.__ Inflow resistance and inflow quantity for Test 14.



Front Face 0.3-m 0.6-m 0.9m

Figure A-45. *Water content distribution in Test 14.*

Test 10: Intentional vertical jointing; 0.25 l/min for 5.5 hours

Test 10 was a replicate of Test 8, excepting that there were 5-mm-wide vertical joints intentionally installed within this test. Tests 9, 10 and 11, 12 were the only test-pairs that were run for different durations (24 hours for Tests 9 and 11 and 5.5 hours for Tests 10 and 12), but this did not seem to have affected the results obtained. There were 1,165.5 kg of blocks installed together with 462.5 kg of Cebogel pellets and the inflow of water occurred at system mid-height at a rate of 0.25 l/min.

Water first exited this test after only 2 hours of operation (30 litres inflow). Flow first occurred in the lower outside corner of the test at the junction of the floor, concrete and pellets. This volume represents 15% of the total and 24% of the air-filled void volume originally present in the pellet fill although some of the water would have entered the volume occupied by the block materials. An hour later outflow began on the lowermost horizontal interface between the clay blocks and pellets. Figure A-46 shows these outflow locations. A total of 15 of the 82.5 litres of water injected into the system flowed out in the course of testing. The 67.5 l retained represents approximately 34% of the total and 54% of the air-filled void volume in the pellet-filled region. The hydration of the clay pellets resulted in closure of the vertical gaps originally present in the system indicating that the pellet materials do provide a confining and compressive force on the blocks. As previously noted, Test 9 experienced a loss of water supply at 15 hours into its operation. This occurred well after Test 10 had been disconnected and so did not affect the flow patterns observed for Test 9 and the patterns of water distribution observed in Test 9 did not show any particular influence of Test 10 (Test 10 showed wetting only at outer perimeter regions with no wetting that even approached the interface with Test 9, as can be seen in Figure A-41.

Flow resistance was monitored and is presented in Figure A-47. This material exhibited essentially no resistance to water inflow, developing only 14 kPa resistance over the 5.5 hours of its operation. This is consistent with a material through which water is freely moving with little interference from the effects of clay hydration. This is in agreement with the water distribution observations made at the time of decommissioning which also indicated that water moved rapidly into the system and encountered little if any interference to its flow. This behaviour is accounted for by the short duration of the test (5.5 hours) as well as the relatively high rate of water inflow, which did not allow the clay to passively take on water and begin to swell.

Test 10 operated for a short-enough period and generated sufficient outflow for outflow rate monitoring to occur. Figure A-47 shows a plot of the outflow recorded and shows that the system is still taking up much more water than it is losing. The presence of the intentional vertical joint openings in the test did not seem to substantially affect the water movement, which is positive given the likelihood of such features existing in an actual application.

On dismantling of this test careful photographic recording of the vertical faces at the downstream face, 0.3, 0.6 and 0.9-m-depth were made and are provided in Figure A-41. It would

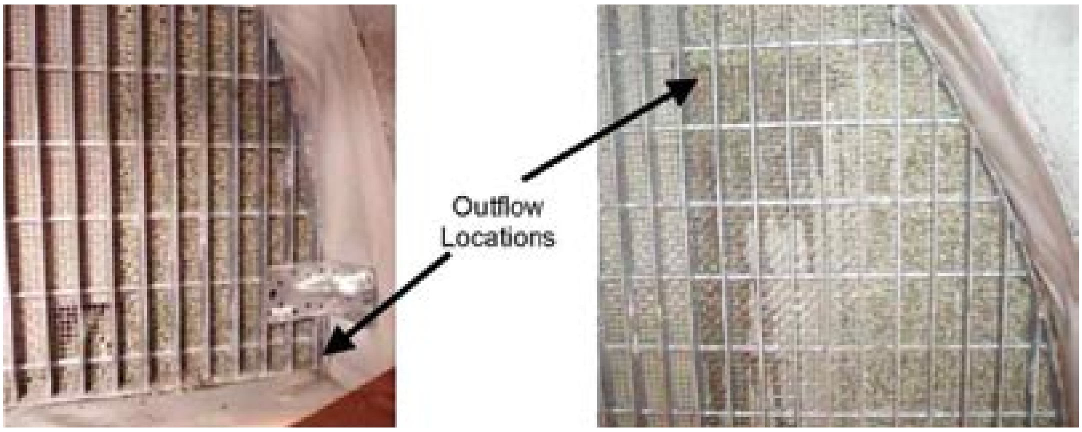


Figure A-46. Outflow from Test 10 at 2 and 3 hours

appear that this inflow rate was sufficiently rapid to quickly move water downwards through the pellet mass and out of the system. Water uptake was limited to a large extent to the areas closest to and below the inlet port and there is evidence of fluid flow vertically downwards through the block joints closest to the inflow point. There was only limited water inflow into the basal and crown regions of the test in the time available.

As the test only operated for only 5.5 hours, extensive sampling was not done and samples recovered were generally associated with the wet pellet materials. The results of water content sampling are presented in Table A-7, showing the variable water distribution expected in a system that has undergone high-inflow for a short time.

Table A-7. Water content data for Tests 6, 10, 12 and 14 (5-hour tests).

Depth	Location*	Test 6 Water content %	Test 10 Water content %	Test 12 Water content %	Test 14 Water content %
Pre-test		**18.7**	**18.7**	**18.7**	**18.7**
Face	A	19	19	19	19
	B	56	65	19	19
	C	58	60	19	19
	D	19	44	19	46
0.3-m	A	19	19	19	20
	B	Wet**	72	58	48
	C	Wet**	62	35	55
	D	19	19	NM	20
0.6-m	A	28	19	19	52
	B	71	70	57	87
	C	59	58	50	63
	D	19	19	19	35
0.9-m	A	19	19	19	38
	B	65	60	57	65
	C	NM	61	48	59
	D	56	19	NM	58

* Locations shown in Figure 5-2

** Physical measurements not made but site was observed to be wet

NM Physical measurements not made, no data on conditions

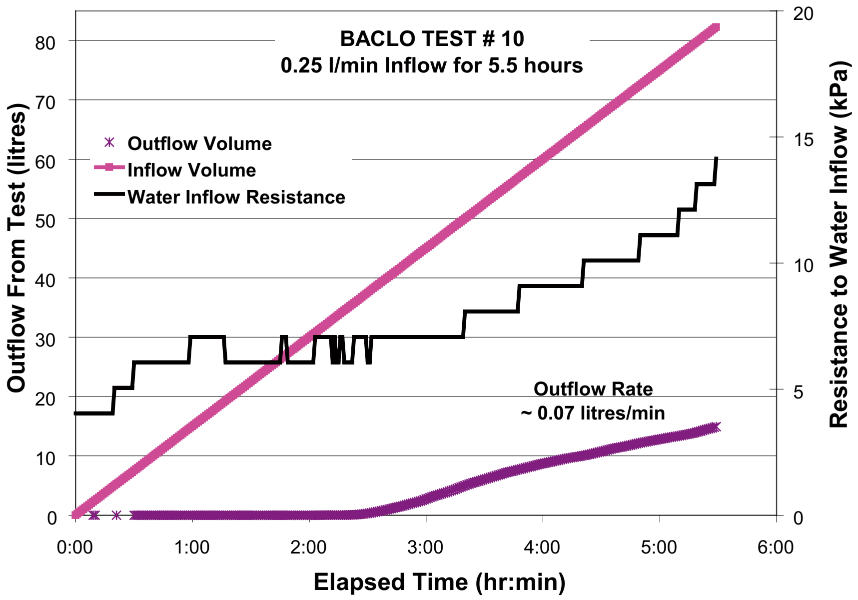


Figure A-47. *Inflow and outflow rates for Test 10*

Test 12: 0.25 l/min for 5 hours

Test 12 replicated Test 10. This was done to determine if the leakage noted in Tests 9-10 had affected the results obtained. Test 12 included the same type of intentional vertical jointing (5 mm gaps) between block packets as were present in Test 10. By replicating Test 10, the representativeness of the water inflow patterns observed for Test 10 could be assessed and any questions regarding the potential influence of loss of constant water inflow conditions in an adjacent region could be addressed. Test 12 had 1,152.5 kg of Friedland clay blocks installed, along with 367.5 kg of Cebogel pellets. The inflow rate was set at 0.25 l/h at the mid-elevation and mid depth of the block assembly.

Water was observed to have reached the front face of the test after 1.5 hours but did not begin exiting until 2.5 hours (37.5 litres inflow), of operation. This volume represents 19% of the total and 27% of the air-filled porosity of the pellet-filled region. Initial outflow occurred at the base of the test where the floor, concrete tube and pellets intersect (Figure A-48). This compares with 2 hours for Test 10 where initial outflow was in the same location. Subsequently, a small quantity of outflow was observed on the lowermost horizontal contact between the clay pellets and clay blocks. As with Test 10, the material being flushed from the test in the first stages appeared to be fine powdered bentonite originating from the pellets. In the 5.5 hours of its operation there had been only 0.12 litres of the 82.5 litres of supplied water that exited Test 12, the remainder was taken into its internal voids. This volume taken into the test represents 42 % of its total and 59% of the air-filled porosity in the pellet-filled region.

The resistance to water inflow by Test 12 is presented in Figure A-51. These results together with the visual observations show a system where water moved rapidly from its injection location into the pellet mass. Once the water encountering the low-porosity, relatively impermeable clay blocks, it moved along the pellet-block interface, either wetting adjacent pellet materials or else exiting the front face of the test. Inflow resistance in this test reached approximately 22 kPa by the time the test was terminated. This is a very low flow resistance but was approximately double that observed for Test 10. The very low flow resistance once again indicates a very low degree of clay self-sealing in the very short term.

The water distribution patterns observed at the time of decommissioning is consistent with the water uptake patterns observed and the differences in the outflow quantities relative to Test 10. Figure A-41 indicates that there was a slightly higher degree of internal wetting in Test 12, relative to Test 10. The volume wet was associated with the higher volume of pellets in the test, providing the test with a higher internal volume for water retention.

Figure A-48. Water exiting lower corner of Test 12 at 2.5 hours

As with the other very short duration tests only a limited number of pellet samples were recovered for water content and density analysis. The results are presented in Table A-6 and provide a general measure of the amount of water that the pellets are able to hold and the effects of water uptake on the density of the pellet-filled volume.

A1.4.2 Tests 16, 18, and 22: 0.25 l/min for 24–48 hours

To compliment the results obtained for very short duration inflow tests done at 0.25 l/min, two tests were run for a 24 hours using the Friedland clay blocks and the Cebogel pellet materials (Tests 16 and 18). As part of a comparison exercise, Test 22 was constructed using crushed Minelco bentonite in place of pellets.

Test 16: 0.25 l/min for 24 hours

Test 16 was essentially identical in construction to Tests 6 and 14 and operated at an inflow rate of 0.25 l/min for 24 hours with ongoing monitoring of water inflow, outflow and resistance to inflow. A total of 1,172.1 kg of Friedland clay blocks and a further 440 kg of Cebogel pellets were installed in the test.

Test 16 experienced water outflow 6 hours and 20 minutes (95 litres inflow) into the test with flow exiting the cell along the 3 horizontal surfaces where the blocks and pellets are in contact. This represents 47% of the total and 70% of the originally present air-filled void volume in the pellets. Within 5 minutes of outflow starting, flow was observed to be exiting the joint at the top of the block assembly and this rapidly established itself as the primary flow path for exiting water. This location was associated with the Friedland clay blocks and considerable erosion was observed in the remaining 18 hours of testing. Figure A-50 provides a photographic record of

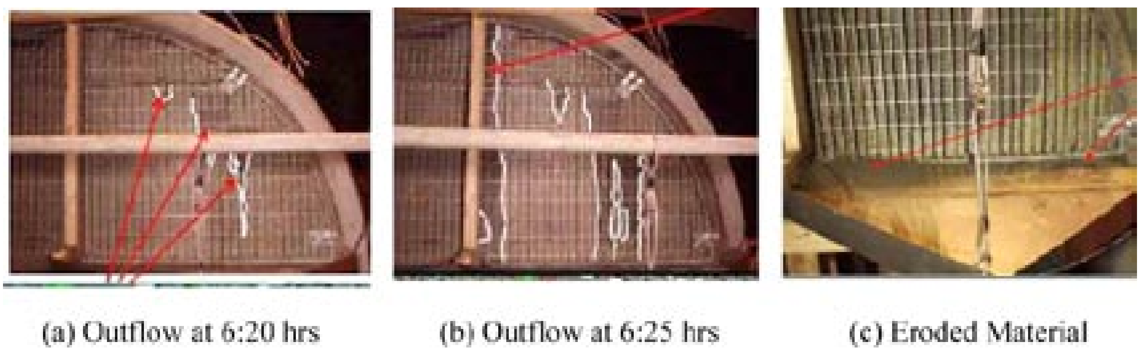


Figure A-49. Wetting at face of Test 16 (arrows on photos indicate the locations where water exited the test).

(a) Front of Test (b) Clay Suspended in Outflow

Figure A-50. *Erosion of clay from Test 16.*

the water outflow locations in this test as well as the nature of the clay being removed by the exiting water. As can be seen in Figure A-50a, the majority of the 11.3 kg of material eroded is from the Friedland clay blocks. The large amount of lighter-coloured suspended material in the outflow water (Figure A-50b) indicates that there is also a bentonite pellet component in the material removed. Much of the Friedland material is the result of surface flow down the face of the block assembly as the water exits the test and not material actually removed through internal erosion.

The resistance to water inflow for the first few hours of test operation is presented in Figure A-42 and the entire evolution of inflow resistance is shown in Figure A-51. The pattern of gradually increasing resistance to water entry for Test 16 is similar to other tests run at this inflow rate. There is a notable dip in the inflow resistance at the time of first water exit from the test but this rapidly recovers and continues to gradually increase to with an apparent trend to stabilize at approximately 80 kPa. This resistance is the same as was observed for systems having an inflow rate of 0.1 l/min and may be a value associated with the swelling pressure developed by the clay pellets.

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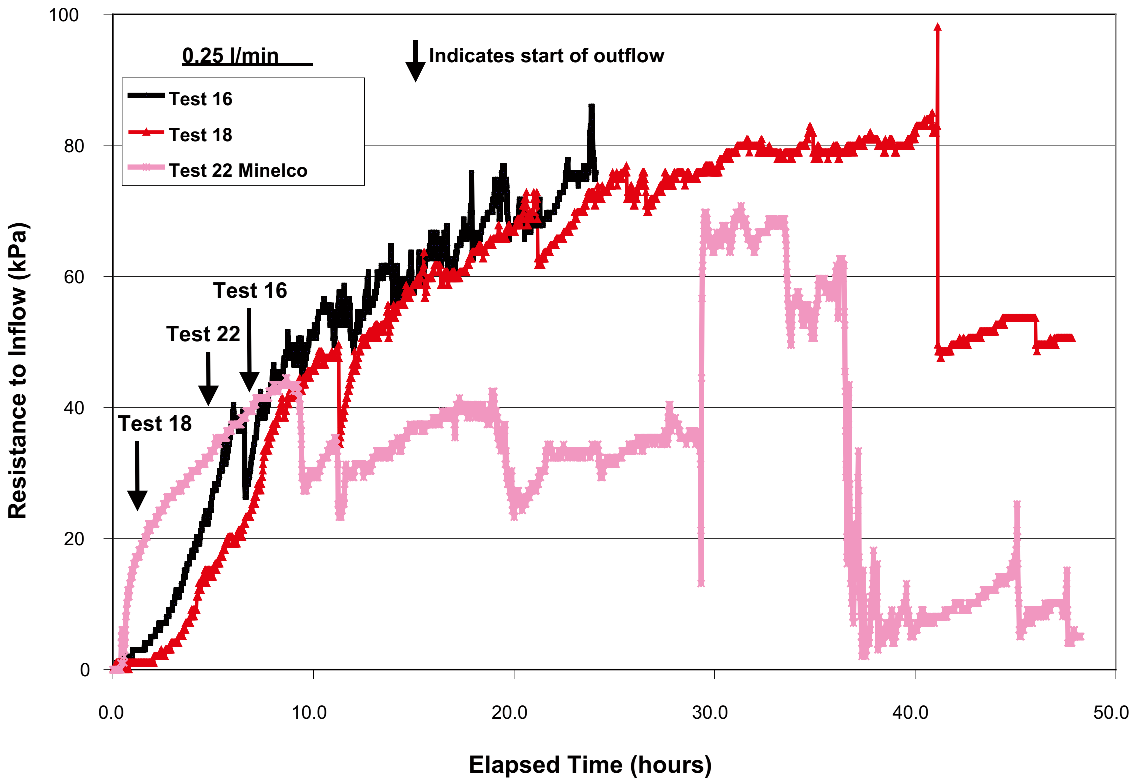


Figure A-51. *Inflow resistance for tests running >24 hrs at 0.25 l/min.*

Test 16 had approximately 95 l enter it before outflow occurred and a further 257 l was input for the remainder of the test. The cell retained 109 l of water, representing 53% of the total and 80% of the original air-filled volume of the pellet-filled region. Figure A-52 presents the view of Test 16 at its front face, 0.3, 0.6 and 0.9-m-depths. The pellet-filled volume shows a high degree of water uptake with only the floor region immediately below the clay blocks remaining dry at the end of testing. The clay blocks show only limited water penetration along joints between blocks and at the outside perimeter of the block assembly.

Disassembly of Test 16 was done such that there was extensive sampling along all 4 sampling depths (Face, 0.3, 0.6 and 0.9-m). Figure A-53 presents a computer-generated water content profile for each of the sections through the test. These data show a system where water has apparently first moved towards the rear of the cell, largely saturating it with the exception of the basal regions below the blocks. It has then moved along the horizontal block-pellet interfaces toward the face of the test chamber. Near the crown of the test, where pellet density will be lowest it flowed rapidly enough to erode a preferential flow path (both visually identified as well as indicated by high water content). For comparison purposes data collected for the same locations as for those test with only a limited number of samples are shown in Table A-8.

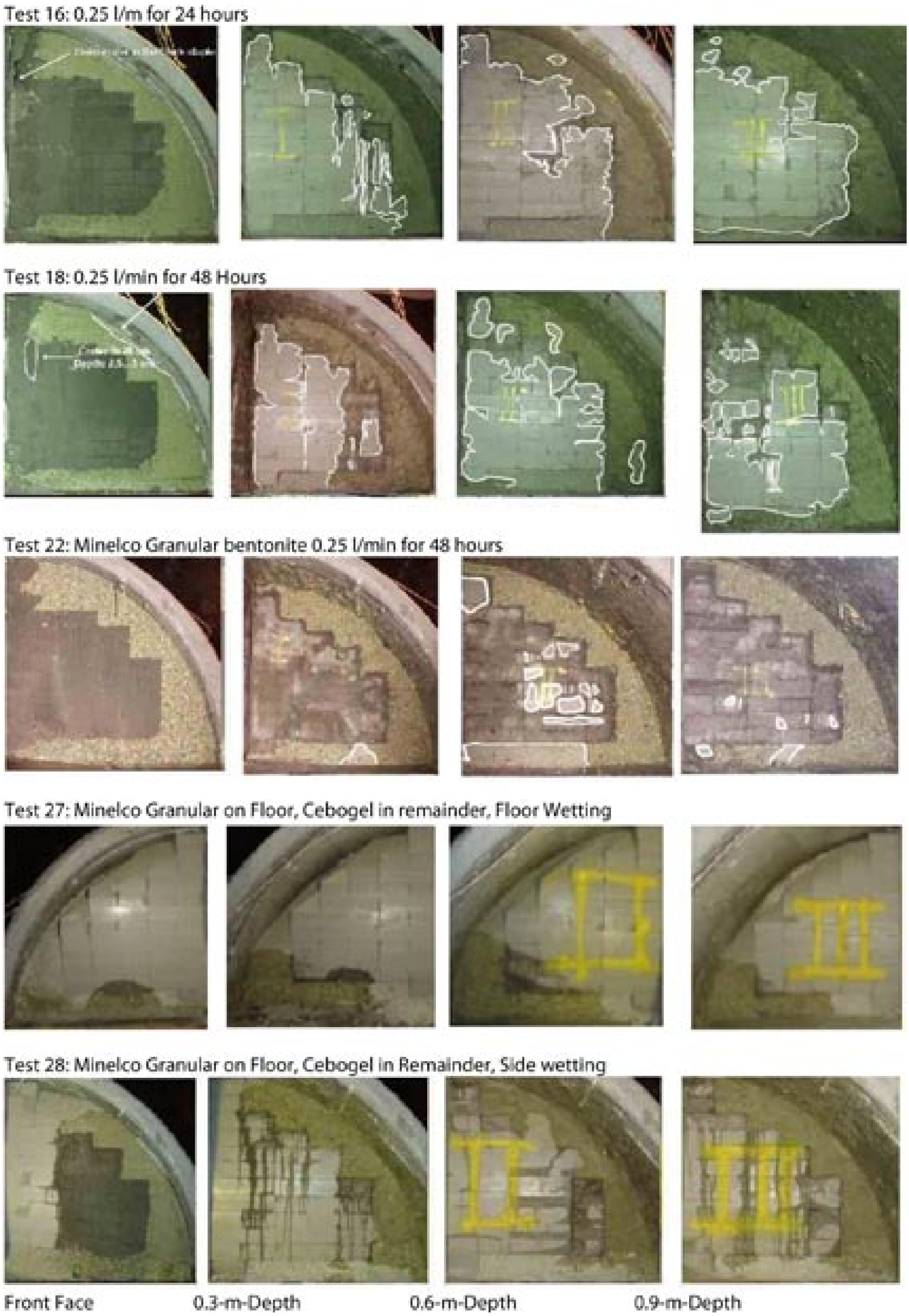


Figure A-52. *Wetting patterns in Tests 16, 18, 22, 27 and 28: 0.25 l/min inflow*

Table A-8. Water content and density data Tests 16, 18 and 22 (24-h tests).

Depth	Location*	Test 16 Water content (%)	Test 18 Water content (%)	Test 22 Water content (%)
Pre-test		**18.7**	**18.7**	**18.7**
Face	A	62	66	80
	B	63	48	81
	C	67	85	69
	D	66	95	110
0.3-m	A	62	58	78
	B	61	66	121
	C	57	65	61
	D	19	20	48
0.6-m	A	65	70	102
	B	72	68	112
	C	57	45	54
	D	19	20	21
0.9-m	A	56	57	74
	B	62	66	87
	C	82	65	65
	D	19	48	21

*As shown in Figure 5-2Test 16: 0.25 l/m for 24 hours

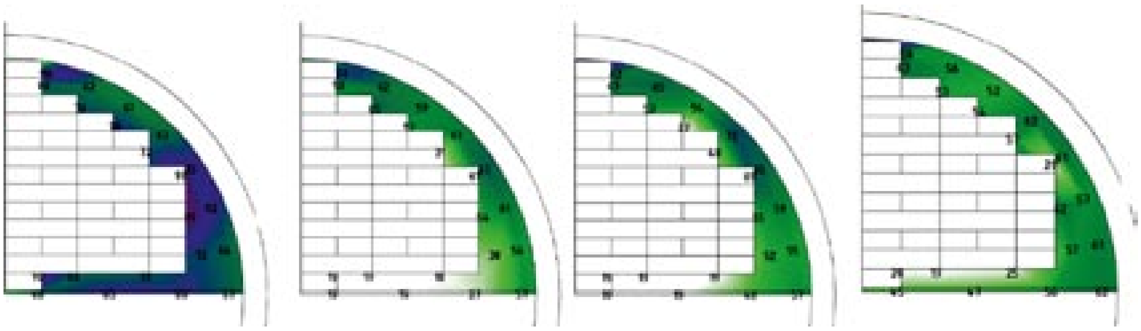


Figure A-53. *Water content distribution in Test 16.*

Test 18: 0.25 l/min for 48 hours

With successful completion of tests run for 5 and 24 hours at an inflow rate of 0.25 l/h, a test was installed that examined the evolution of the system from 24 to 48 hours. This test is the longest duration undertaken at 0.25 l/min and is intended to complete the assessment of inflow rate on short-term block-pellet stability. Test 18 had 1,204.8 kg of Friedland clay blocks and 415 kg of Cebogel bentonite pellets installed. The inflow, outflow, erosion and resistance to inflow were continuously measured for the 48 hours that this test operated.

Water exited the front of the test after only 70 minutes of operation (17.5 litres inflow), exiting the test from the lower corner where the floor, concrete tube and pellets intersect. This volume represents 9% of the total and 14% of the air-filled pore volume of the pellet-filled region of this test. This is the same location that several other tests observed first outflow and likely represents water that has moved along the pellet-concrete contact until reaching the front of the test. This location continued to produce a limited amount of outflow for most of the test's duration but had very little eroded material associated with it. By 7 hours into the test water was exiting the system at the lowermost horizontal contact between the clay blocks and the pellet materials. At 24 hours into the test, flow was being dominated by a single point source of flow located near the top of the test just above the last horizontal layer of blocks (Figure A-54). This was nearly the identical location where channelling flow was observed in Test 16 (0.25 l/min for 24 hours) and considerable erosion of block materials was observed. Most of the material removed was as a result of water flowing vertically down across the face of the blocks once it exited.

The resistance to water inflow was monitored and is presented in Figure A-51. The resistance measured is essentially identical to that observed for Test 16 during its 24 hours of operation. The resistance to inflow increased more-or-less steadily trending towards an equilibrium value of approximately 80 kPa until approximately 40 hours into the test when a very marked drop in inflow resistance occurred (from 80 kPa to 50 kPa). This is likely associated with the development of a flow channel having much lower resistance to flow than previously present and may involve only a small amount of additional erosion in the major flow channel near the top of the test.

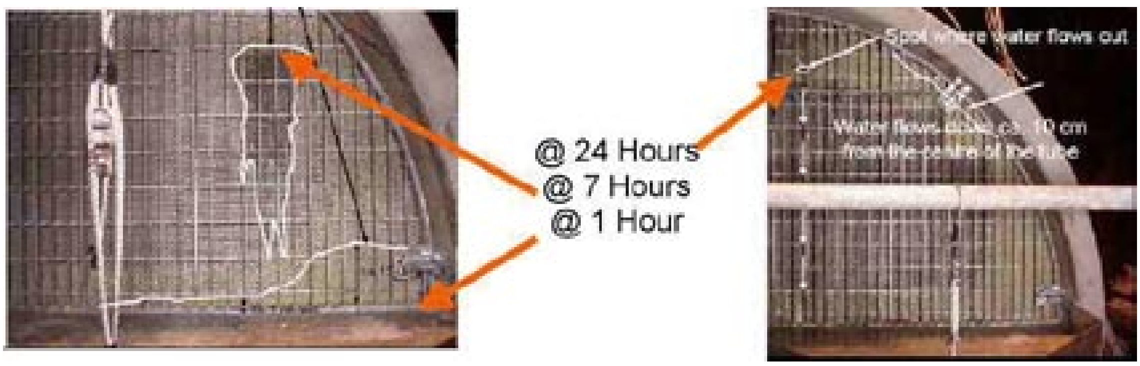


Figure A-54. *Wetting at face of Test 18.*

Dismantling of Test 18 was undertaken in the same manner as the other tests done in this study and involved systematic sampling of the pellet materials at 0, 0.3, 0.6 and 0.9-m-distance from its front face. Figure A-52 shows the wetting patterns observed in the test at the time of decommissioning. The test has obviously developed a higher degree of saturation than was observed in the test that ran only 24 hours. There was still a notable pocket of dry pellet materials present below the clay blocks but its volume was much reduced. The clay blocks also showed a higher degree of wetting showing a pattern consistent with a mass that is taking up water through its perimeter and undergoing gradual hydration.

Test 18 had only 17 litres of water added before outflow was observed by overall it had approximately 716 litres of water pumped into it. Of this approximately 530 litres subsequently exited and was collected leaving 186 litres of water within the test at the end of 48 hours. This represents a 76% through-flow rate and an estimated end-of-test degree of saturation of approximately 97% of the total porosity of the pellet-filled region and more than 100% of the available volume in the pellet-filled region. There must therefore have been substantial water intake into the blocks and wetted block materials on the downstream face that did not get taken into account in the retained water volume estimations.

In the course of test disassembly there was an extensive sampling process undertaken in order to develop a detailed picture of the water distribution within the pellet materials as well as to determine what changes may have occurred in the density of the pellet-filled volume. Figure A-55 presents a computer-generated contour plot of the water content and dry density distribution in each segment of Test 18. The data collected for the same locations as for tests where there was limited sampling undertaken are also provided in Table A-8.

The water content data show a system that is very similar to Test 16 in terms of its water uptake patterns. As with Test 16, water seems to have moved first towards the rear of the test cell and then moved forward along the pellet-block interfaces until exiting the front face. The very high water content observed at the front crown region of the test corresponds with the erosional feature observed in the test (Figure A-52) and is likely associated with the movement of water into the crown regions and preferential flow through the lower-density, less resistant material located there.

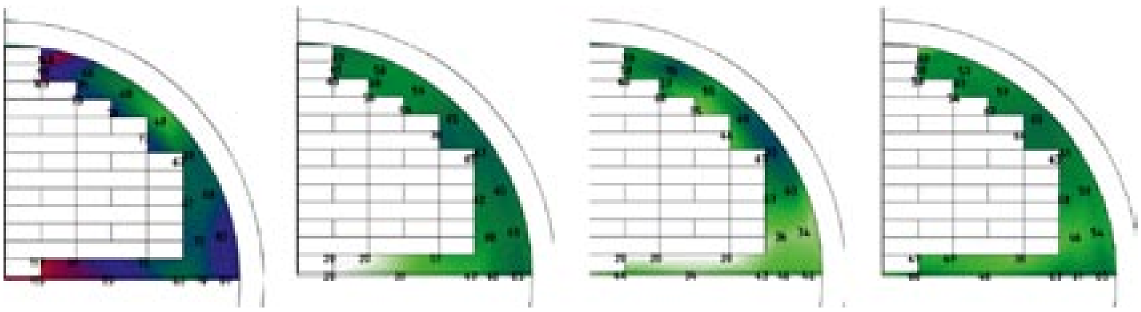


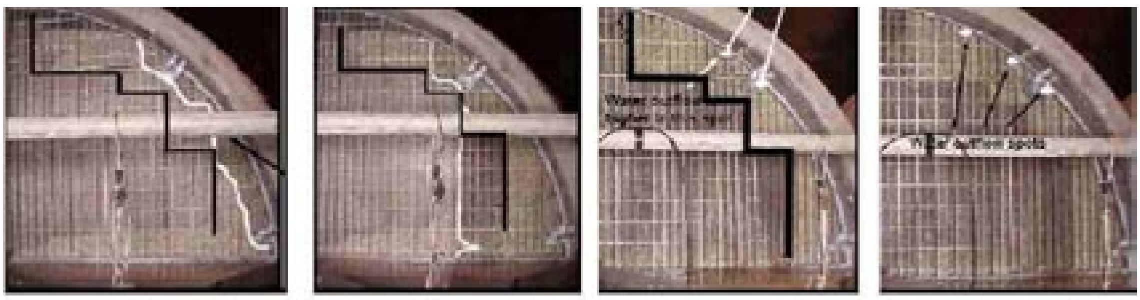
Figure A-55. *Plot of water content and density in Test 18.*

Test 22: 0.25 l/min for 48 hours: minelco granular

Test 22 was a replicate of Test 18 where Minelco granular bentonite rather than Cebogel pellets was used to fill the region below the blocks and between the blocks and the concrete tube. The intention was to examine the water uptake and erosion-resistance of this alternative to pellet materials. This test contained 1,073.9 kg of Friedland clay blocks and 390 kg of Minelco granular bentonite. Water was supplied to this test via the mid-height, mid-depth water port mounted in the wall of the concrete tube used to contain this test. The inflow, outflow, erosion and resistance to inflow were continuously measured for the 48 hours that this test operated.

Water was observed exiting this test after 4 to 5 hours of test operation (675 litres inflow, exact outflow time missed). This inflow volume represents 26–32% of the total and 36–44% of the original air-filled porosity of the pellet-filled region. By 5.5 hours into the test the wet region occupied a belt 8,120 mm wide and 2/3 of the length of the contact of the granular fill with the concrete tube. At 5.5 hours, most of the water appeared to be coming from a source about halfway along the length of the contact (see Figure A-56a). By 7 hours the zone of wet pellets had extended all the way to the clay blocks and about ¾ of the height of the test (Figure A-56c). Water was still predominantly exiting from the same location as previously. It should be noted that at 6.5 hours into the test a small water leak was detected at the connection of the inlet (in floor) and the wooden floor plate (steel lined) at the base of the test. This was a small leak and its output was captured, total outflow over 48 hours was only 6 litres, less than 1% of the water supplied in the course of the test. By the time that 24 hours had elapsed, the wetting had progressed to include all of the front face and water was exiting from several locations at the clay-concrete interface (Figure A-56c), generally at a higher elevation than was observed previously (Figure A-56d). The outflow location remained essentially unchanged for the last 24 hours of the test. The inflow/outflow records indicate that there was approximately 261 litres of water retained by the test, however the total available porosity within the pellet-filled volume is only 169 litres and this volume was clearly not saturated at the end of testing. This means that the leak in the system either was not as small as indicated (which is not considered likely given the location of the leakage), or more likely there was a very large quantity of water taken into the Friedland clay blocks at the front of the test, as can be seen in Figure A-52.

Resistance to inflow was monitored and is presented in Figure A-51. The first 10 hours of test operation saw a smooth and steady rise in the resistance to inflow to approximately 45 kPa. After this time the resistance to flow became very erratic with periods of higher, but generally lower resistance to inflow. For a brief period (336 hours) the resistance increased almost instantaneously from 35 kPa to 65 kPa but then just as quickly dropped back to an average of 10 kPa where it remained until the end of the test. This type of behaviour is indicative of a material that has multiple flow paths that are not entirely stable, changing path length and relative size with time. The drop to a resistance of 10 kPa indicates the formation of one or more stable flow paths



(a) 5 Hours (b) 7 Hours (c) 24 Hours (d) 30 Hours

Figure A-56. *Water outflow from Test 22 (changing outflow locations as system took on water).*

directly along the concrete-clay boundary where there is little ongoing erosion. An estimated 12.5 kg of material was lost through erosive activity (captured mass). Much of this material was lost as the result of outflow water washing along the outside surface of the Friedland clay blocks. There was also a component of the granular bentonite lost. This test lost the largest quantity of material of any of the tests done at this flow rate (3.8% of total material removed in 24 hours).

Dismantling of Test 22 was done in the same manner as all previous tests with extensive sampling undertaken to establish the distribution of water and density within the granular-filled regions. Figure A-52 presents the wetting patterns of the test at the end of test. There is only a very small portion of the granular bentonite that is not wet (below blocks near centre of floor region) and a few very small isolated pockets. The granular bentonite was much more effective in transmitting the water throughout the fill than any other test conducted for the same duration. The Friedland clay blocks also showed a higher degree of wetting than had been observed in previous tests.

Test 22 was extensively sampled in the course of decommissioning and a computer-generated plot of these data for each of the testing depths (Face, 0.3, 0.6 and 0.9-m) is presented in Figure A-57. Additionally, the data collected for the same locations as for tests were there was limited sampling undertaken are provided in Table A-8.

The water content measurements show a system that has taken on considerable water in the region immediately adjacent to the water inflow point and the regions immediately above it but has not been able to transmit substantial water into the lower half of the test. It would seem that the Minelco granular bentonite was able to form a fairly effective seal immediately below the inflow point and forced the water upwards into the crown regions where pellet density was likely slightly lower and there was less resistance to water movement. The Minelco granular materials have previously been observed to be much more rapidly reactive (swell more quickly) than pellet materials, which would support such an interpretation. An alternative explanation of the tendency for water to move upwards in the test is that there could be a slightly increasing particle density as the floor is approached, resulting in an increased resistance to water movement downward. Regardless of the process causing this movement, the result is a system that tends to direct water movement towards the crown, where the potential for erosive, channelling flow is higher.

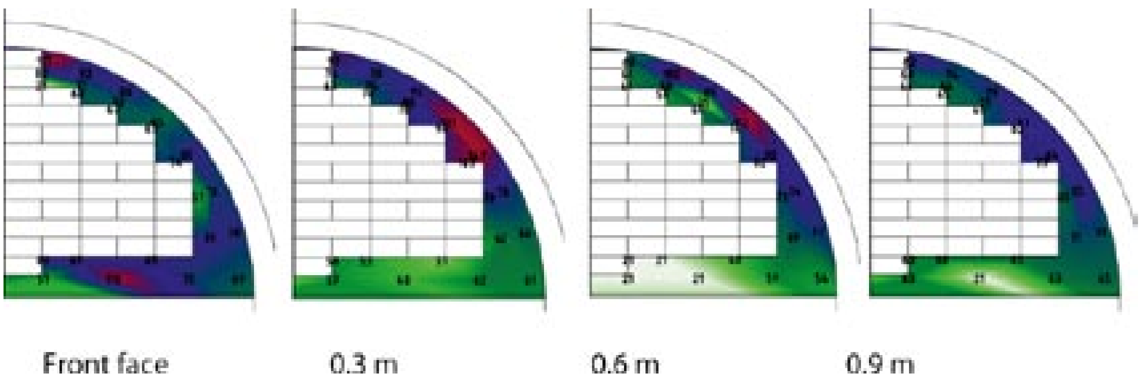


Figure A-57. *Water content data for Test 22.*

Test 27: 0.25 l/min for 48 hours; minelco, cebogel and floor inflow

Test 27 involved a system constructed using Minelco granular bentonite for the flooring material beneath the clay block assembly. Once the floor and blocks were installed Cebogel bentonite pellets were used to fill the remaining space between the blocks and concrete walls of the test cell. A total of 164 Friedland clay blocks were installed, 156.25 kg of Minelco granular bentonite and 260 kg of Cebogel pellets. Water was supplied to the floor of this test via a floor-mounted water inlet located as shown in Figure A-36. The inflow, outflow, erosion and resistance to inflow were all measured over the course of the 48 hours of testing.

This test began to have water exiting its front face after 2 hours and 3 minutes of operation. It took another 48 minutes before sufficient water exited the system to allow flow into the weighing system. Water exited first along the pellet-floor interface at the centre-left of the cell (see Figure A-58). Within a few minutes water was slowly seeping from a length of the floor of the test set-up but wetting seemed to be most active in the region of first outflow with wetting progressing up into the crushed bentonite. Flow rapidly evolved to a single region of outflow close to the original location with considerable material erosion and pulsating flow as water damned and broke free near the front face of the cell. All flow was moving through a single channel along the crushed bentonite-block interface region below the block assembly. By the time that 5 hours of testing had elapsed the outflow rate from this test was 0.245 l/min for a system having a nominal inflow rate of 0.250 l/min. Flow continued unhindered at this rate until 24 hours had elapsed at which time outflow rate checks were made. Outflow continued at 0.245–0.250 l/minutes for the second day of operation and continued to contain a considerable sediment load. At 48 hours of testing water outflow was checked a final time before being discontinued and was still 0.245l/min. Water supply was then discontinued and dismantling of the test began.

At the time of dismantling Test 27 wetting was clearly limited to a small volume near the base of the test. Figure A-61 shows the vertical profiles through the test during decommissioning at depths of 0, 0.3, 0.6 and 0.9 m from the front face and water has clearly initially moved to the outside of the test set-up at the base and then gradually moved upwards along the outer perimeter. Total volume wet in the course of the test was very limited and a preferential pathway was clearly established early in the test and remained stable for the entire time.

Resistance to water inflow was monitored for the entire test duration and is presented in Figure A-59. The data shows a system that very rapidly established a preferential flow path that was likely somewhat erosive in nature in the period immediately following its development (as indicated by rapid drop in resistance). It is likely not particularly erosive once the flow path was established since the flow resistance as very stable and ongoing erosion and increasing flow channel would likely have been accompanied by further reduction of flow resistance. This was supported by the observation that outflow occurred from a single point at the face of the test for essentially the entire test.

Once established at 3 hours, outflow rate was typically 95–100% of inflow and had entrained within it a considerable amount of particulate material. This material contained two distinctive

Figure A-58. Wetting at face of Test 27.

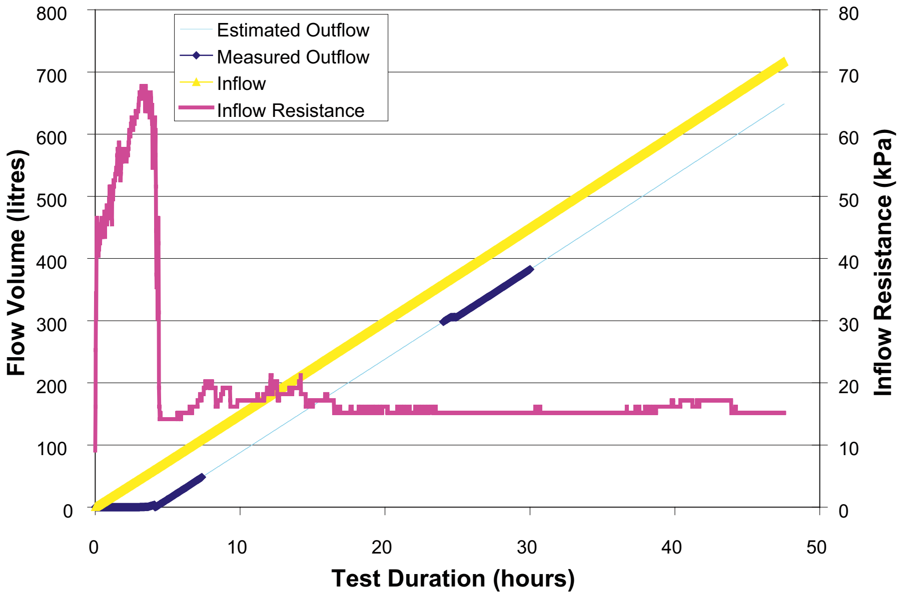


Figure A-59. *Inflow and outflow quantities and resistance to inflow for Test 27.*

components; fine-grained dark-coloured particles that showed no particular cohesive characteristics and a coarser grained light-coloured particulate that broke down only slightly even when left soaking in outflow water. These materials originated from the Minelco granulated bentonite used in the test and the coarse mixture of hard granules and weakly cemented sediments proved to be quite prone to water-induced erosion. Figure A-60 shows these particles as they appeared in the outflow tray of the test.

An effort was made to collect all of the coarse eroded materials from the outflow system over the course of testing and in excess of 5.4 kg of material collected, representing more than 4 % of the granular (Minelco) mass. The total amount removed is certainly higher than 4% as there were suspended fines removed that were not captured in the sediment collection system. An estimate of the total mass removed based on suspended solids and eroded mass collection is presented in Section 7 of this document. Erosion was continuous for the 48 hours of testing with ongoing removal of material could make stability of this material problematic over the longer-term.

At the end of this test the system was disassembled and water content samples were taken in order to develop a water distribution pattern for this test (Figure A-61). As could be seen visually these data show a system that has undergone very limited wetting in the course of its operation and what wetting has occurred has been largely limited to the granular bentonite, and to a lesser extent the pellet materials. There has been essentially no water uptake by the Friedland clay blocks.

Figure A-60. *Coarse particulate materials eroded from Test 27. (Note coarse, weakly cemented white particles and finer dark eroded materials).*

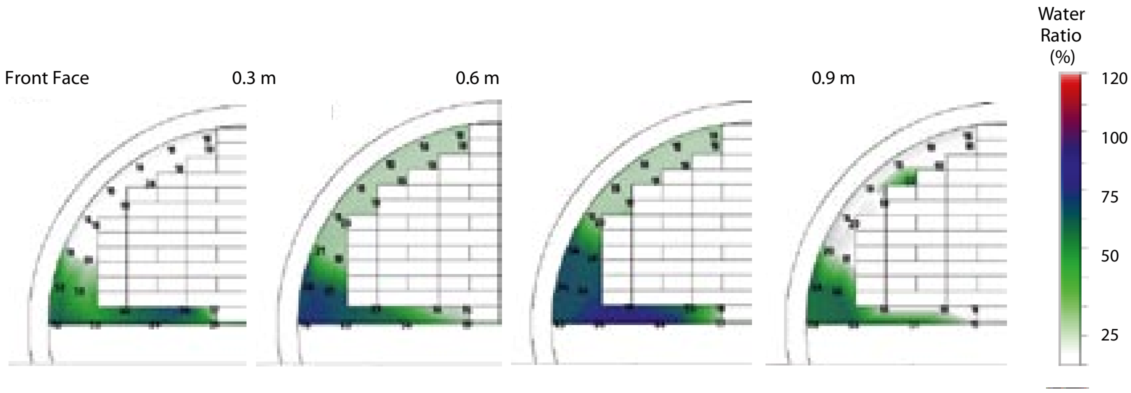


Figure A-61. Plot of water content profiles in Test 27.

Test 28: 0.25 l/min for 48 hours; minelco on floor, cebogel above floor

Test 28 involved a system constructed using Minelco granular bentonite for the flooring material beneath the clay block assembly. Once the floor and blocks were installed Cebogel bentonite pellets were used to fill the remaining space between the blocks and concrete walls of the test cell. A total of 164 Friedland clay blocks were installed, 156.25 kg of Minelco granular bentonite and 260 kg of Cebogel pellets. Water was supplied to the cell at its mid-height and mid-distance into the block assembly via a water inlet that penetrated the concrete cylinder. The inflow, outflow, erosion and resistance to inflow were all measured over the course of the 48 hours of test operation.

This test began to have water exiting its front face after 5 hours of operation. It took several more hours before sufficient water exited the system to allow flow into the weighing system. Water exited first along the pellet-block horizontal interface at the outside of the block assembly with some preferential wetting evident at block contacts (Figure A-62). Flow gradually evolved from wetting of the pellet-block interface region to a single point of outflow close at the concrete-pellet interface at approximately the same elevation as the water injection port. Essentially all flow was moving through this single channel after 24 hours of test operation and it remained unchanging for the remaining 24 hours of test operation. At 24 hours the outflow rate from this test was 0.235–0.245 l/min for a system having a nominal inflow rate of 0.250 l/min and remained in this range until test termination at 48 hours.

At the time of dismantling Test 28 wetting was clearly well distributed with only small regions still remaining dry, notably the Minelco pellet material below the blocks and a small region near the crown of the test. Figure A-63 shows the vertical profiles through the test during decommissioning at depths of 0, 0.3, 0.6 and 0.9 m from the front face and water has clearly well distributed throughout the test. It was noted that many of the pellet-filled areas within the test had seen

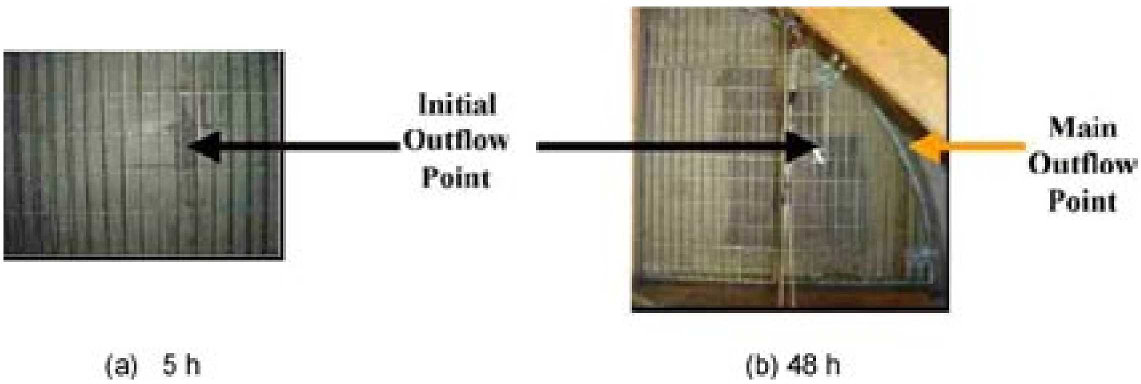


Figure A-62. Wetting at face of Test 28.

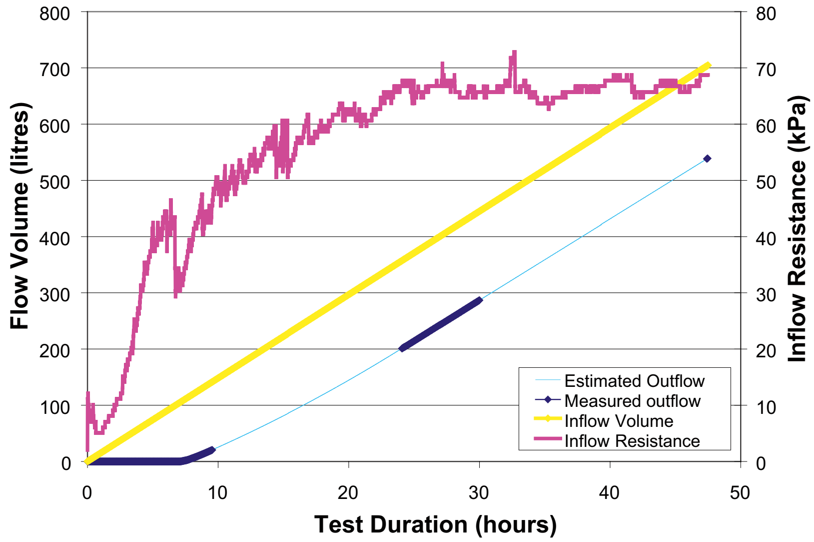


Figure A-63. *Inflow and outflow quantities and resistance to inflow for Test 28*

some water supply but not enough to allow them to swell and homogenize with the outer, wetter materials. It would therefore appear that the water initially moved quite freely through the pellet-filled portion of the system, but with fairly rapid swelling of the pellets there was an interruption of water supply to these locations, leaving them only partially hydrated or in a few areas with pockets of dry pellets. Water did not successfully enter the granular bentonite located at the base of the test; only a small region saw any water uptake over 48 hours of water supply.

Resistance to water inflow was monitored for the entire test duration and is presented in Figure A-63. The data indicates that the system has developed a stable flow path through which essentially all the water entering the system is moving. There is little evidence of substantial ongoing water uptake by the backfill pellets or blocks (indicated by parallel inflow and outflow lines).

Consistent outflow from a single point persisted for essentially the entire test duration. Once established after 6–7 hours, outflow rate was typically 95% of inflow and had entrained within it only a very small amount of bentonite gel. This material was clearly Cebogel clay and had both the appearance and texture normally associated with hydrated bentonite. The low rate of erosion measured for this test is consistent with other tests where water established a pathway along the concrete-pellet interface.

An effort was made to collect all of the coarse eroded materials from the outflow system during the test and in total 0.5 kg of material was captured, representing 0.2% of the pellet mass having been removed over a 48 hour period. There is also a fines component that was lost during the course of testing but this is not believed to have totalled a significant mass, as the exiting water was extremely clear.

In the course of dismantling this test, detailed water content sampling was undertaken in order to quantify the visual observations regarding water distribution within the test. Figure A-64 presents these data and shows a test where water uptake by the pellet materials was extensive but did not extend substantially into either the underlying granular bentonite or the Friedland clay blocks. The granular materials clearly acted as an effective barrier to water movement, forcing water accumulation to occur within the pellet-filled region. The clay block materials showed only limited water uptake along the contacts with the pellets and some evidence of water movement along the joints between the blocks (Figure A-52). The establishment of a preferential flow path at the pellet-concrete interface also makes it unlikely that this test would ever have developed an internal flow path through the clay blocks.

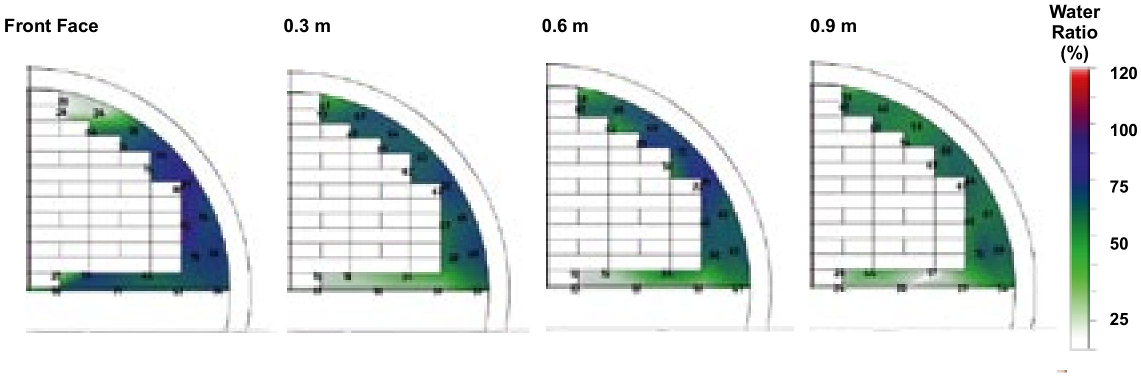


Figure A-64. Water distribution at the end of Test 28

Test 29: 0.25 l/min for 48 hours; side inflow for 2 non-isolated cells

Test 29 involved a system constructed using Minelco granular bentonite for the flooring material beneath the clay block assembly. Once the floor and blocks were installed Cebogel bentonite pellets were used to fill the remaining space between the blocks and concrete walls of the test cell. A total of 184 Friedland clay blocks, 550 kg of Minelco granular bentonite and 312.5 kg of Cebogel pellets were installed. This test differed from other similar tests in that it involved the full test set-up (both halves of test chamber) and did not have a bentonite mat between the halves to prevent water from moving from one side to the other. This test was intended to provide an indication of what type of water movement would occur in a tunnel where water was entering only at a limited location on one side of the tunnel. This information can then be used in developing a test plan for the larger (1/2-scale) tunnel simulations planned at Äspö. Water was supplied to the cell at its mid-height and mid-distance into the block assembly via a water inlet that penetrated the concrete cylinder. The inflow, outflow, erosion and resistance to inflow were all measured over the course of the 48 hours of test operation.

This test had water exiting its front face after only 70 minutes of operation. It took several more hours before water outflow began to stabilize in both rate and location. Water initially exited at the lower right corner of the test chamber where the floor, pellets and concrete wall intersected but rapidly shifted to the horizontal block-pellet interfaces, stepwise exiting higher from the test assembly as time progressed. Within 24 hours flow had shifted to a single point at the concrete-pellet interface at an elevation close to that of the inflow port located approximately 0.6 m into the test assembly. Outflow from this interface location was steady, clear (little eroded material) and did not change location for the remainder of the test. Figure A-65 shows the location of outflow and wetting during the test operation. There was also water moving along the pellet-block horizontal contacts as can be seen in Figure A-65 but this volume was not sufficient to result in fluid movement into the collection system. Water outflow from the test was monitored for extended periods through the outflow mass measurement as well as a number of spot-checks. Outflow rate was measured to be 0.260 l/min after 24 hours of operation for a system having an inflow rate of 0.263 l/min and remained in this range until test termination at 48 hours. This indicates essentially no ongoing water uptake by the system once the preferential flow path develops.

Figure A-65. Wetting patterns at face of Test 29 during testing.

At the time of dismantling Test 29 wetting was clearly well distributed with only small regions still remaining dry, notably the Minelco pellet material below the blocks and a small region near the crown of the test. Figure A-66 shows the vertical profiles through the test during decommissioning at depths of 0, 0.3, 0.6 and 0.9 m from the front face and water has clearly well distributed throughout the test. It was noted that many of the pellet-filled areas within the test had seen some water supply but not enough to allow them to swell and homogenize with the outer, wetter materials. It would therefore appear that the water initially moved quite freely through the pellet-filled portion of the system, but with fairly rapid swelling of the pellets there was an interruption of water supply to these locations, leaving them only partially hydrated or in a few areas with pockets of dry pellets. Water did not successfully enter the granular bentonite located at the base of the test; only a small region at the pellet-granular contact saw any water uptake over 48 hours of water supply.

Also of importance to note was that water did not move from one side of the test assembly to the other, indicating a clear hydraulic disconnect between the two sides. This is significant in that it indicates that water may initially tend to flow along the side of the tunnel it enters rather than moving across to saturate adjacent materials. This means that there could be substantial pockets of isolated and unsaturated pellet materials in a tunnel section. This hydraulic disconnect between the two sides of a backfilled "tunnel" also provides confidence in the results obtained in this testing series as it indicates that it is possible to run parallel tests at different inflow rates without being concerned with short-term interaction between the two sides.

Resistance to water inflow was monitored for the entire test duration and is presented in Figure A-67. The data shows a system that has developed a stable flow path and essentially all the water entering the system is being transported directly out with little or not ongoing water uptake by the system beyond that which is drawn in via suction the wet region to that which is not yet saturated.

Consistent outflow from a single point persisted for essentially the entire test duration. Once established, outflow rate was typically 99% of inflow and had entrained within it only a very small amount of bentonite gel. This material was clearly Cebogel clay and had both the appearance and texture normally associated with hydrated bentonite. The system had rapidly evolved into one where very little erosion occurs in the course of transmitting water along the concrete-pellet interface, a condition that is consistent with other tests. As the granular and block materials were not involved in the water outflow then the eroded materials must have come from the pellets. It is estimated that 3.5 kg of material was removed from the test over 48 hours of flow. This represents approximately 1.5% of the pellet material.

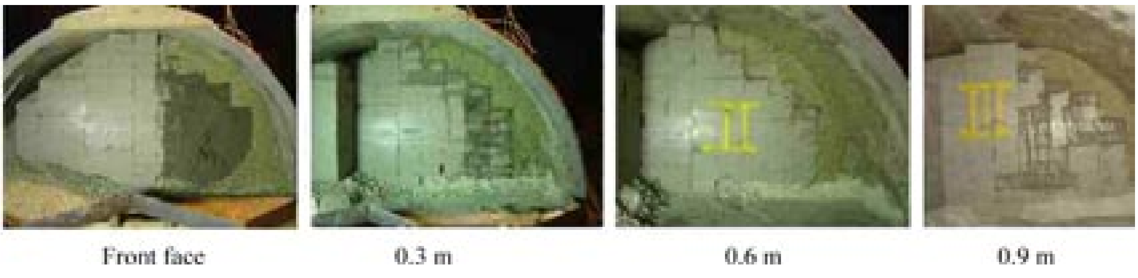


Figure A-66. *Vertical wetting patterns in Test 29 at time of dismantling.*

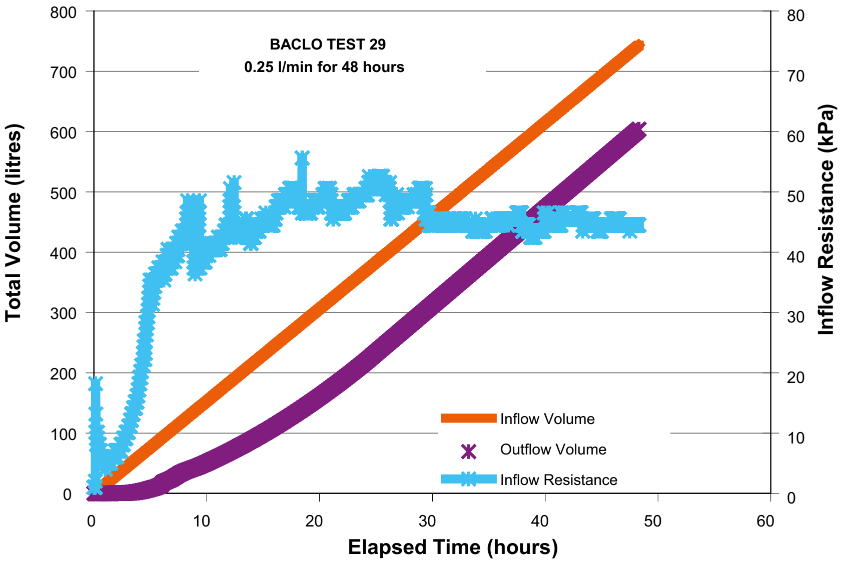


Figure A-67. Inflow and outflow quantities and resistance to inflow for Test 29.

At the time of dismantling of the test extensive sampling was done in order to quantify the visual observations. The water content plot provided in Figure A-68 shows a system that has essentially no hydraulic connection between the two sides of the cell. Water has moved forward along the pellet-block interface to a limited degree but most of the flow has occurred along the concrete – pellet contact at approximately the same elevation as the water was supplied to the cell. Once reaching the downstream face, the water flowed down the face and began to wet the materials closer to the base but this wetting was very limited. The test has demonstrated that water will apparently remain close to the site where it enters the cell and will not readily migrate laterally within it. This is potentially important in a tunnel environment where there is a need to be able to estimate the pathway(s) that water will typically take from ingress to exit at the downstream face.

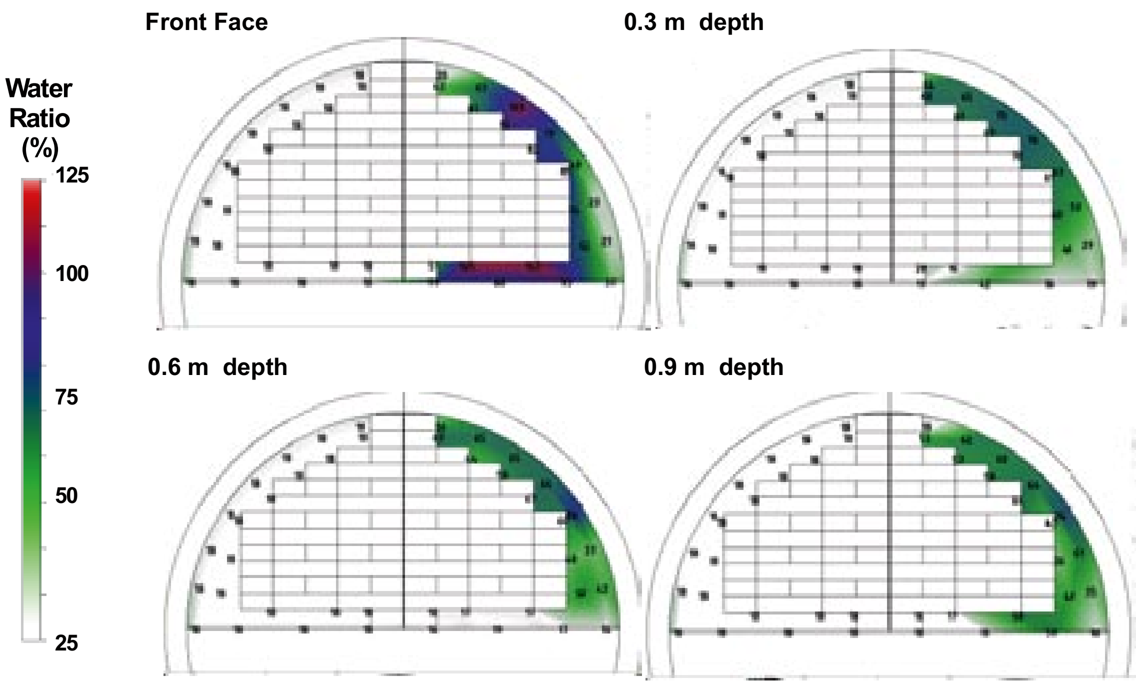


Figure A-68. Water distribution at the end of Test 29.

A1.5 Tests having water inflow of 0.5 l/min

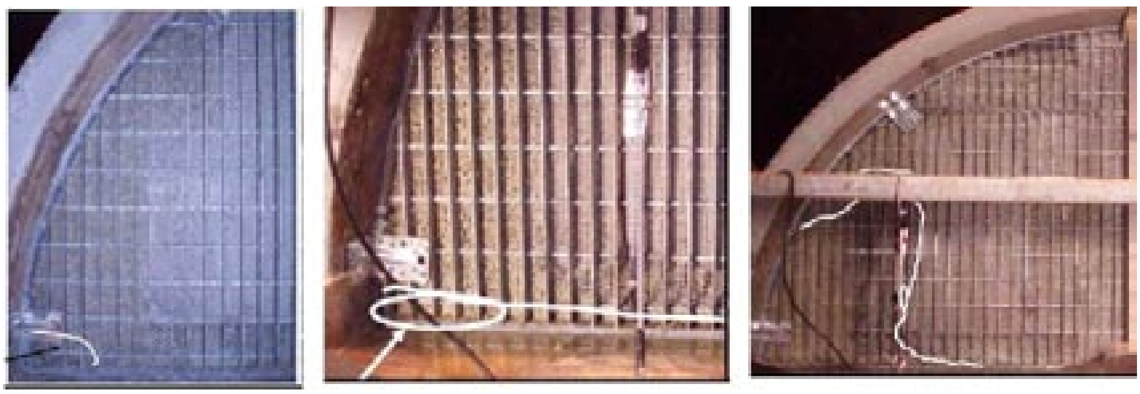
Three tests were operated at a water inflow rate of 0.5 l/min, Tests 13, 20 and 24. They simulate a situation where an unremediated, high inflow feature was present and ongoing backfill operations were happening. They provide an indication of the time that the backfilling operations might have before water entering the pellets would begin to have an effect on the region downstream. The first, Test 13 operated for only 4.5 hours, the second, Test 20 was run for 100 hrs. These two tests provide valuable information about the immediate and longer-term behaviour of the backfilling system under high inflow conditions. The third test operated at this inflow rate was Test 24 that had water supplied to the pellets on the floor of the test. Test 24 was intended to operate for 24 hours but technical difficulties made data collected after approximately 7 hours of questionable value.

Test 13: 0.5 l/min for 5 hours

This test was constructed in the same manner as the other tests done as part of this study) with 1,204.8 kg of clay blocks and 405 kg of Cebogel pellets installed. It was operated at 0.5 l/min inflow from a single point source located at the mid-height and mid depth of the test assembly. Resistance to water inflow, wetting patterns, water outflow and erosion were all monitored and samples were recovered for water content and density analyses in the course of test dismantling.

Wetting was observed in 20 minutes (10 litres inflow) and water actually exited the test set-up after 44 minutes (22 litres of inflow), of operation, flowing from the contact between the floor, concrete wall and pellets. This is the same location as was observed in several of the tests conducted at an inflow rate of 0.25 l/min. At the time that water was actually flowing out of the test there had only been approximately 12% of the total and 18% of the air-filled voids within the pellet-filled region filled with water. Water outflow progressed with an increasing area at the base of the test producing seepage and an increasing quantity of wet pellet material being evident near the base of the test.

Figure A-69 presents a series of photographs showing the locations where water was exiting the test at various times. Within 2 hours of starting the test, the majority of the outflow was coming from the phreatic surface of the clay pellets. Water was moving in an essentially unrestricted manner through the unsaturated pellet-filled region and as the pellets swelled and generated resistance to flow the flow surface moved upwards in the test.



a) 44 minutes b) 2 hours c) 5 hours

Figure A-69. *Water outflow from face of Test 13.*

Resistance to inflow for Test 13 is presented in Figure A-70. Resistance did not increase appreciably in the course of the test, reaching only 22 kPa by its completion. There was a trend towards slowly increasing resistance with time, perhaps as a result of increasing degree of water saturation or changing flow path as the lowermost regions of the test saturated and began to swell. Despite the rapid inflow (and outflow) rate of this test, there was little observable erosion of material from the test. The materials removed were dust and fines originally present in the pellet fill. They were removed only as the phreatic surface passed through the region they occupied. In total only 87.5 grams of fines were measured as having been removed from the test and at the end of the test the rate of erosion was discernibly decreasing with time (1.3 g/l at end of test). This means that unless new, more erosive flow paths developed the test could expect to lose only about 40 grams of material per hour. Extending this observation to a tunnel environment where backfilling were interrupted this would indicate that the system should be relatively stable for at least a short time. The development of a stable, non-erosive pathway for water movement is also advantageous for ongoing backfilling operations as it allows for methods to collect the outflow to be utilized that will not compromise backfill performance.

The distribution of water within this test was mapped through extensive sampling at the time of dismantling. The results of these analyses are presented in Figure A-72 and shows that water has moved to the rear of the test chamber in considerable quantities, flooding most of the pellet volume before flow began to move forward. Given that the inflow-outflow rates were essentially equal shortly into the test it is likely that flooding of the rear-most portion of the test occurred early in its operation. The water moved preferentially along the concrete-pellet interface as is indicated by the high water contents measured in that region. At 0.5 l/min inflow there is little of the test volume that had not rapidly seen water at least briefly before swelling of the clay would have make its movement more difficult. At this inflow rate there is little resistance to inflowing water and little time between the start of water influx (or placement of material in a system seeing water influx at time of inflow) and the exiting of water from the front face some 0.6-m-distant from the inflow point. For additional comparative purposes, water contents obtained at locations A-D (Figure 5-1) are provided in Table A-9.

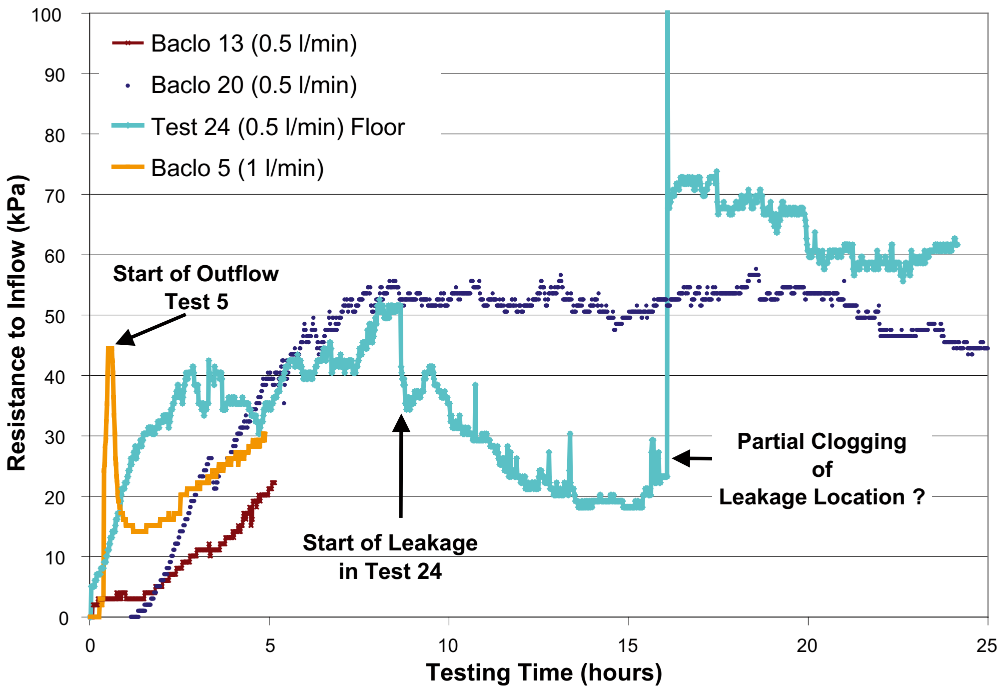


Figure A-70. *Resistance to water inflow: Tests 13, 20, 24 and 6.*

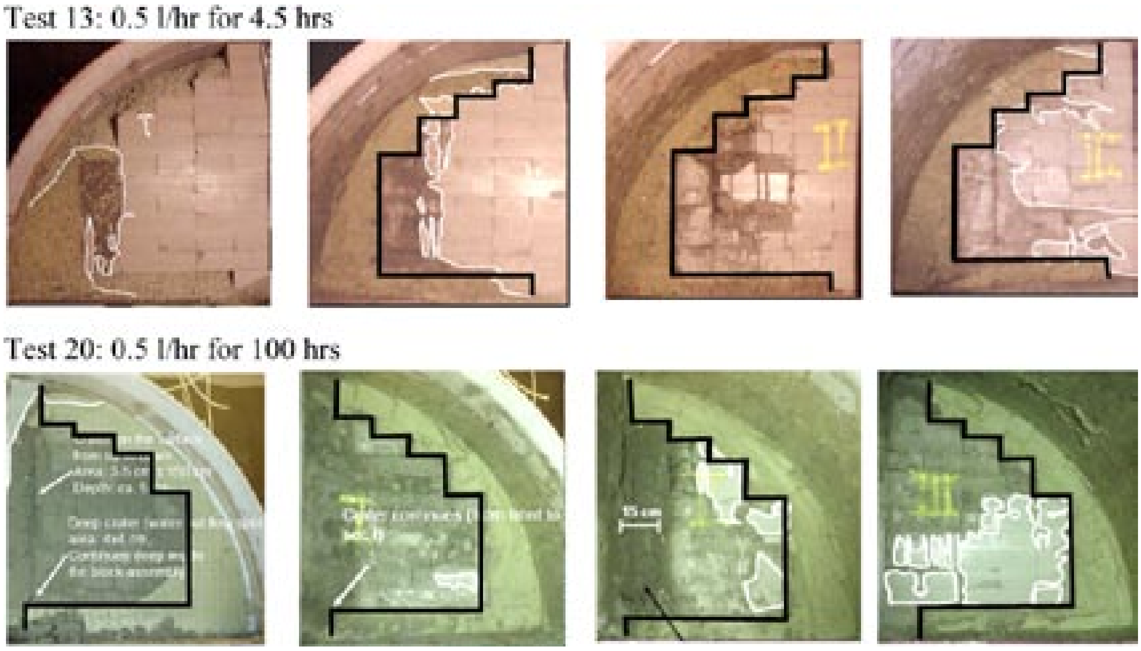


Figure A-71. Wetting patterns in Tests 13 and 20 (0.5 l/min) (showing extensive wetting and development of preferential flow channels).

There was nearly full wetting of the pellet filling within the 5 hours that this test operated. There remained only a small pocket of dry pellet material in the crown region and in a small area below the blocks near the downstream face of the test. Another small area of unsaturated pellets was located in the upper half of the pellet fill near the downstream face and adjacent to the concrete tube. This is likely due to the relatively short period of test operation and the flow of water towards the front of the construction. There is evidence of water penetration into the joints between the blocks closest to the pellets in the lower to mid-elevations. This is of limited extent and given the short duration of this trial, it is unlikely that this water represented more than a few litres water volume. The end-of-test water uptake by this test is estimated to be 120 litres, representing 63% of the total and 96% of the original air-filled void volume in the test although some of the water had obviously moved into the clay blocks.

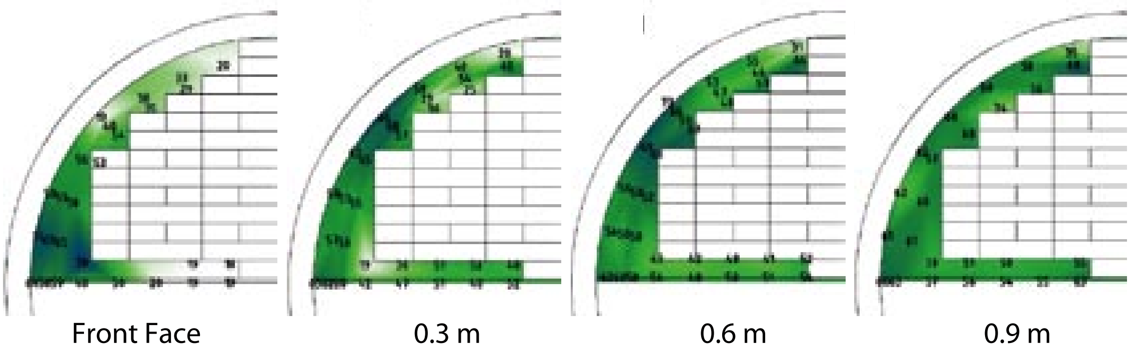


Figure A-72. End-of-test water content distribution in Test 13 (sections at 0, 0.3, 0.6, 0.9 m distance from front face).

Table A-9. Water content data for Tests 13, 20, 24, 5 (0.5 and 1.0 l/min).

Depth	Location*	Test 13 Cebogel 0.5 l/min (5h) Water content %	Test 20 Cebogel 0.5 l/min (100h) Water content %	Test 24 Cebogel-Floor 0.5 l/min (7h) Water content %	Test 5 Cebogel 1.0 l/min (4.5h) Water content %
Pre-test		**18.7**	**18.7**	**18.7**	**18.7**
Face	A	20	19	19	19
	B	56	Wet**	61	19
	C	64	Wet**	80	66
	D	19	Wet**	73	19
0.3-m	A	40		53	19
	B	66		57	Wet**
	C	65		69	Wet**
	D	50		53	19
0.6-m	A	54		62	40
	B	73		67	77
	C	62		65	53
	D	50		56	19
0.9-m	A	58	68	19	65
	B	60	69	64	67
	C	66	67	70	62
	D	52	61	65	67

* As shown in Figure 5-2.

** Physical measurements not made but materials had a higher water content than at the start of the test.

NM – Physical measurements not made.

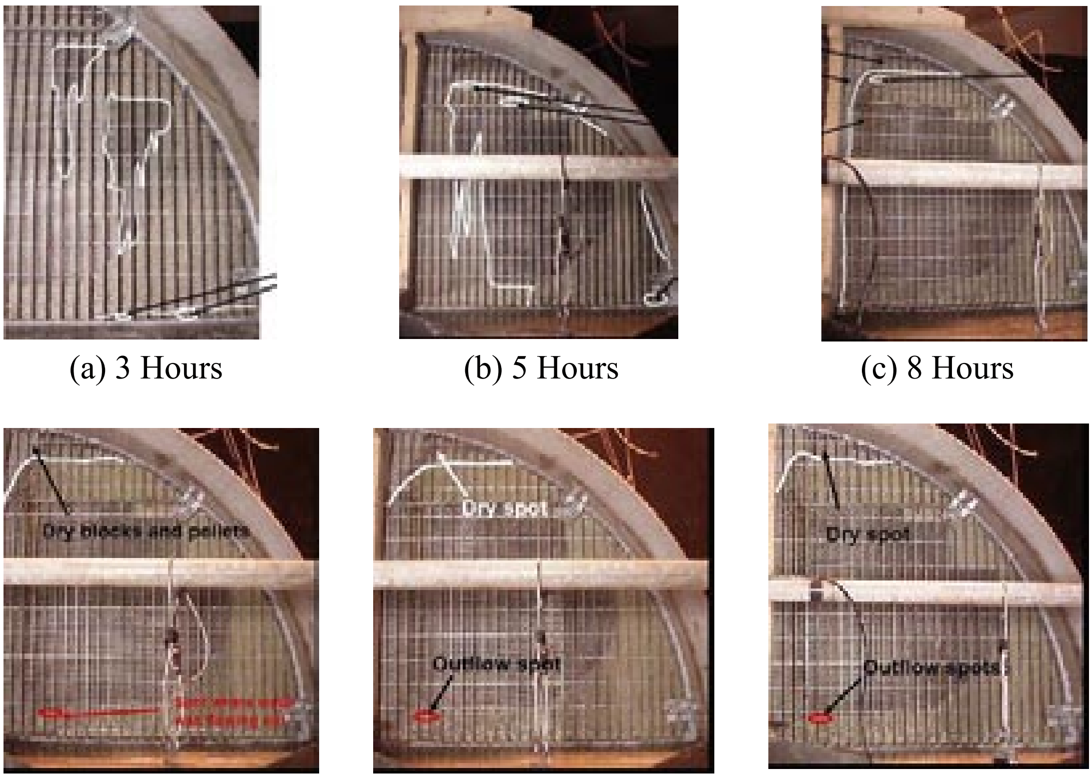
Test 13 was the first of the extensively sampled constructions in this study. A very comprehensive series of samples were recovered for water content and dry density determinations. The results of these analyses are presented in Figure A-72 shows that water has moved to the rear of the test chamber in considerable quantities, flooding most of the pellet volume before flow began to move forward. Given that the inflow-outflow rates were essentially equal shortly into the test it is likely that flooding of the rear-most portion of the test occurred early in its operation. The water moved preferentially along the concrete-pellet interface as is indicated by the high water contents measured in that region. At 0.5 l/min inflow there is little of the test volume that had not rapidly seen water at least briefly before swelling of the clay would have make its movement more difficult. At this inflow rate there is little resistance to inflowing water and little time between the start of water influx (or placement of material in a system seeing water influx at time of inflow) and the exiting of water from the front face some 0.6-m-distant from the inflow point. For additional comparative purposes, water contents obtained at locations A-D (Figure 5-2) are provided in Table A-9.

Test 20: 0.5 l/min for 100 hours

Test 20 had the highest water inflow quantity of any of the tests carried out in this study. In total 3,000 litres of water was injected into this test. A total of 1,204.8 kg of Friedland clay blocks and 410 kg of Cebogel pellets were installed in this test. Water was supplied via a single point source located at the mid-height and mid depth of the test assembly. Resistance to water inflow, wetting patterns, water outflow and erosion were all monitored and samples were recovered for water content and density analyses in the course of test dismantling.

Water was observed exiting the test chamber after 160 minutes of operation at which time 80 litres of water had entered the system. This volume of water would fill 43% of the total and 64% of the original air-filled volume in the pellet-filled region. Outflow occurred at the same location as for Test 13 and several other tests conducted as part of this study (at the contact between the floor, concrete wall and pellets). This test exhibited numerous changes in the location of water outflow during the course of its operation. Figure A-73 shows the evolution of outflow location with time. Within 24 hours of starting the test a stable flow path had developed and remained for the rest of the test. This pathway was unusual in that it was located at the base o the clay block assembly at its contact with the clay pellets and obviously represents a flow path that passes through the clay block assembly.

Resistance to inflow was monitored for the entire duration of the test and is presented in Figure A-74. The resistance to outflow showed a fairly smooth rise until it reached approximately 55 kPa at 10 hours (300 litres inflow) into the test. In this phase of the test, the flow paths were not consistent and the system was clearly in the process of undergoing initial hydration. For the next 10 hours (until 20 hours into the test) resistance remained quite constant indicative of a stabilization of flow path with little erosive activity. Resistance to inflow dropped sharply at approximately 24 hours to 45 kPa and then again at 40 hours to 30 kPa. Each of these steps are interpreted to represent changes in flow paths within the test as water sought and found new, less restrictive passages. There was also a degree of internal erosion associated with these steps since there was no outward evidence of flow path changes after 24 hours of operation. For the final 60 hours of testing, the system showed a gradual decrease in resistance to inflow but maintained the same outflow exit location. The observed resistance measurements correspond to the development of gradually larger flow path, likely associated with gradual internal erosion of materials (Friedland clay).



(a) 3 Hours (b) 5 Hours (c) 8 Hours

(d) 24 Hours (e) 48 Hours (f) 100 Hours

Figure A-73. *Development of outflow paths in Test 20 (showing initial unstructured seepage and subsequent tightly channelled flow).*

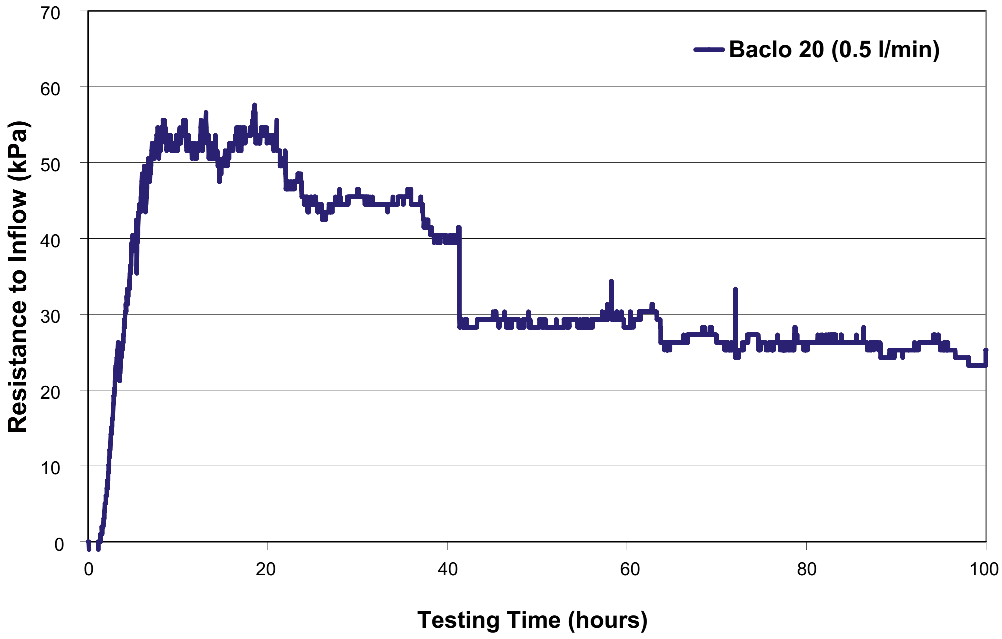


Figure A-74. *Outflow resistance for Test 20.*

Disassembly of Test 20 occurred in the same manner as all other tests that were extensively sampled, with sampling at the downstream face, 0.3, 0.6 and 0.9-m depth. Figure A-71 shows the wetting patterns observed during this process. After 100 hours of water influx the entire pellet-filled volume was apparently saturated and considerable wetting of the blocks, especially adjacent to the joints between them had occurred. Only a small region near the rear of the assembly was still in its original moisture state. Test 20 showed very extensive surface and internal erosion of the Friedland clay materials. At the face of the test there was a considerable volume of Friedland clay removed as the result of water flowing down the face of the test from near the top. It was not possible to accurately determine the quantity of material removed by it is likely more than 2 kg. On the downstream face, water exiting a pipe approximately 5-10 mm-diameter formed between clay blocks and at the clay block – pellet interface had eroded a considerable volume of Friedland clay, leaving a small (~ 40 mm diameter) crater in the surface. The pipe extended horizontally into the block assembly until a depth of 0.6 m was reached. At 0.6 m depth the pipe opened up into a vertical feature eroded at the contact between the sections of clay blocks and extending upwards for the entire height of the block assembly. The eroded volume was approximately 150 mm wide and had an estimated depth of 350 mm for a length of 0.75 m, or a total of 5.6 litres.

Removal of clay from the test by the exiting water in Test 20 was monitored by collecting a number of outflow samples and analysing them for solids content. Figure A-75 presents the erosion measurements and shows a clear, early state of high erosive activity from the start of water outflow until 10 hours (corresponding to achieving peak inflow resistance) erosion rate then decreased steadily until some point between 24 and 50 hours into the test, when erosion rate became essentially constant. It should be noted that the outflow rate measured for this test indicated that water was exiting at a rate of approximately 0.6 l/min. This difference in supply rate is not likely to be important to the results observed but it does mean that 20% more water was sent through this test than was intended. The pattern of the erosion-rate data is consistent with the flow resistance data provided in Figure A-74 showing resistance decrease at 24 (also associated with development of lower outflow point shown in Figure A-73) and again at 40 hours stabilizing at a very low value after 40 hours of testing. The total quantity of eroded material was not determined due to the very high volume of water that went through the test. A total of 10 kg of coarser-grained eroded material was captured in the outflow system and physically measured but considerable material was lost before it could be weighed. Based on the measured erosion rate it is estimated that 25–30 kg of material may have been removed. That mass represents approximately 2% of the total mass of the backfill placed.

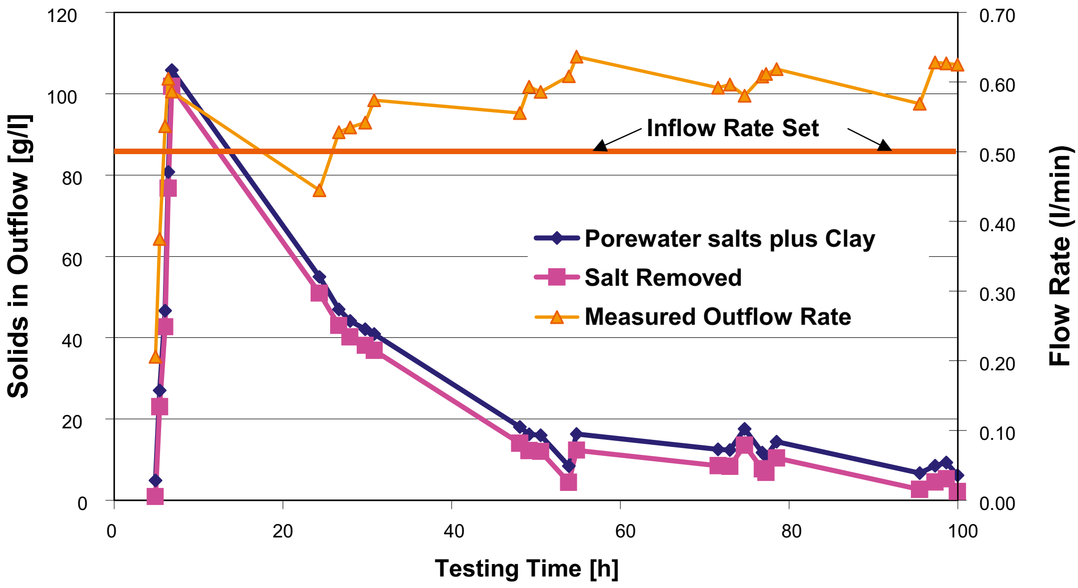


Figure A-75. *Flow rates and rate of material removal in Test 20.*

Test 20 experienced the highest amount of flow-induced erosion observed in this study and highlights the potential problems of installing backfill in a high-inflow region and also the relative ease with which Friedland clay can be removed if an internal flow path is developed. For comparison to other tests done in this study water content values for locations A-D (Figure 5-2) are presented in Table A-9.

Test 24: 0.5 l/min for 24 (7) hours, floor inflow

Test 24 was the second test conducted where water was supplied to the floor of the test cell. It contained 1,073.9 kg of Friedland clay blocks and 455 kg of Cebogel pellets and had water supplied to the pellets on the floor at 0.5 l/min. Resistance to water inflow, wetting patterns, water outflow and erosion were all monitored and samples were recovered for water content and density analyses in the course of test dismantling.

Water began exiting the downstream end of this test after only 3 minutes of operation (1.5 l water supplied), less than 1% of the air-filled porespace in the pellets. The water moved directly from its entry point to the front of the test, a distance of approximately 0.6-m. Following initial arrival of outflow at the downstream face, seepage was very limited and began to shift toward the centre of the cell. By two hours into the test, seepage had established itself approximately 10 cm from the left side of the test at the interface between the clay blocks and granular material.A considerable amount of eroded material was contained within the outflow. Between three and four hours flow shifted horizontally to the right-hand side of the clay blocks and then back towards the centre of the test, still at the interface between the blocks and the pellets. Considerable fines were included with the exiting water. At four hours into the test water began to exit from between the clay blocks at the right side of the assembly close to the top of the outermost portion of the test, water also began to exit the test in the lower outside corner of the test assembly. Between 5 and 7 hours into the test, outflow was primarily from its outside lower corner and the pellets could be seen to be gradually wetting up along the outside of the system. Figure A-76 shows the wetting patterns visible on the front face of the test during its operation.

At approximately 7.5 hours into the test water reached an unsealed port approximately ¾ of the way up the wall of the concrete tube occurred and this became the preferred flow path out of the test. Prior to this leakage occurring the test had approximately 225 litres of water supplied to it and 130 litres had exited, leaving 95 litres in the test chamber (45% of total and 69% of air-filled porespace in the pellets). After leakage began there was still collection of outflow

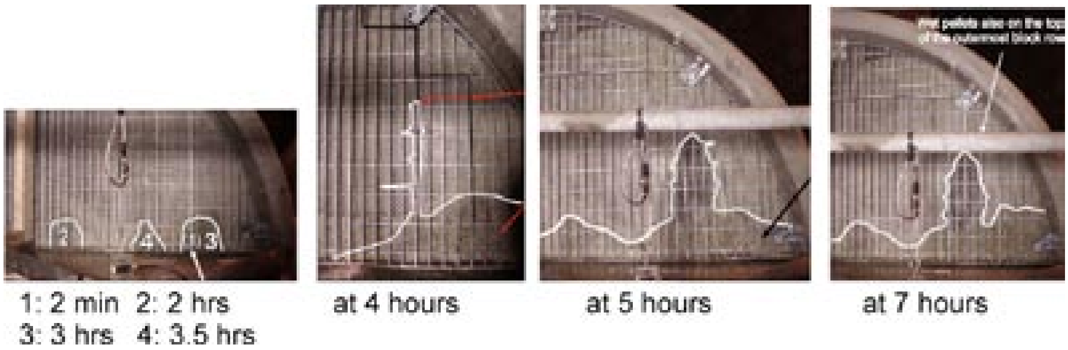


Figure A-76. Wetting at front face of Test 24 (photos showing outflow locations on floor of assembly and upward movement of water evidenced at front face of assembly in first hours of water inflow).

from the face but only 40 or the 480 litres supplied over a 16-hour period exited from the face and at 24 hours there was no outflow occurring at the face of the test. The water exiting the opening in the side of the test cell contained considerable eroded clay but it was not possible to quantify it to any degree of certainty. It is notable that the test contained a volume of still-dry pellet material at its crown and in the front-most region of clay blocks (Figure A-77). This is the result of preferential water flow elsewhere and water uptake in other regions would be driven by suction-related forces.

Resistance to inflow developed by this test for the first 8 hours of its operation was generally similar in pattern and magnitude to other inflow tests as can be seen in Figure A-70. Resistance reached approximately 50 kPa at 8 hours into its operation, but then experienced a progressive decay to approximately 20 kPa by 15 hours. This decay can be attributed to the system beginning to leak from the unsealed port in the concrete and development of a preferential flow path to this location. At approximately 16 hours there was an almost instantaneous increase in resistance to 70 kPa followed by a gradual decrease back to 60 kPa. The drop in inflow is likely associated with ongoing erosion of the block and pellet material as water moved from the inlet to the outlet (leakage) location. It is also interesting to note that the water is not flowing along the shortest path length out of the test chamber (0.6 m along pellet-floor contact) but is moving upwards through at least 0.6 m of the block assembly and then through at least 0.15 m of pellet materials before exiting the system. Of the resistance measured at least 10 kPa can be attributed to the hydraulic head developed through water flowing "up" to the outflow location. Pathway resistance is therefore more in the order of 50 kPa at the end of the test.

Removal of material in the course of this test was substantial. During the first 6.5 hours of operation at least 1.4 kg of clay was removed by the water exiting the test. Most was removed from the pellet-filled regions (0.4% of pellet mass). The material removed was predominantly "dust" and fines from the pellet-filled regions but there was a notable quantity of the coarser and

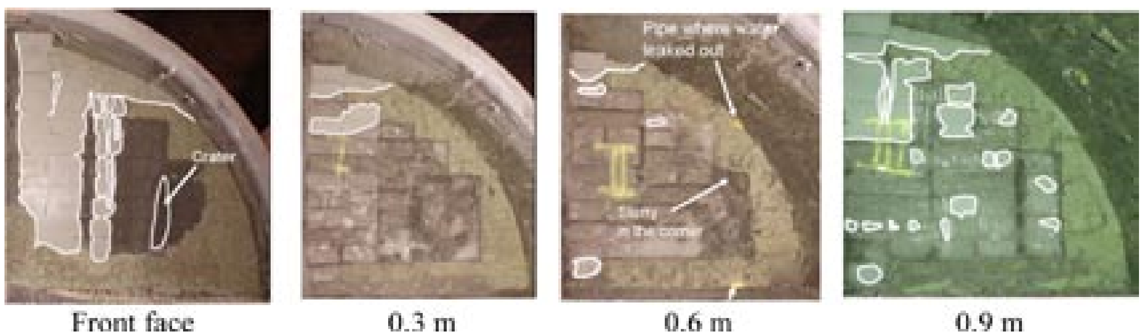
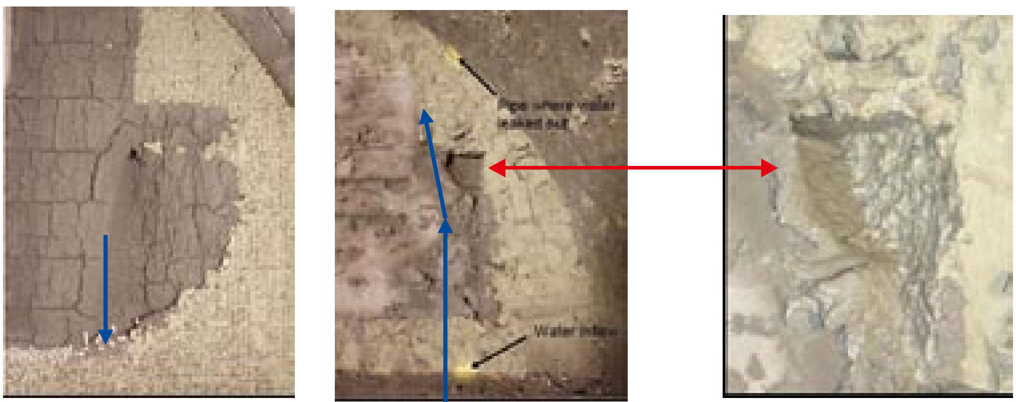


Figure A-77. Wetting patterns in Test 24 (0.5 l/min via floor) (extensive erosive and piping features developed together with substantial material removal).

darker coloured Friedland material. Friedland materials were likely from the region immediately above the inlet port at the base of the test cell. After approximately 8 hours the rate of erosion greatly increased with development of an outflow channel on the face of the blocks (see Figure A-77 and Figure A-78). This channel feature is likely the source of the 40 litres of outflow collected between 7.5 hours and 24 hours. After 24 hours the outflow at the face ceased and flow channelled to the leakage point where volume measurements were not made. This leakage point was connected with the region at 0.6-m-depth where an entire section of block material was removed, leaving only residual (gel-like) material behind (Figure A-78). Loss of this material represents approximately 6 kg of material (1 clay block). Beyond the material lost at the upper right portion of the block assembly there was clear vertical erosion of block materials at the joint between the right-most stack of blocks and the group adjacent to it. It is easily conceivable that the material lost along these flow paths represented at least another block of Friedland clay (6 kg). There is less evidence of bentonite pellet removal by outflow so it would seem that flow from the clay block region to the leakage point was via a relatively small and stable flow channel. Total erosion of material from this test is estimated from physically collected sediment is approximately 13.4 kg (~1% of total backfill mass), but may be higher.

Test 24 did not operate entirely in the manner planned as the result of the unplanned exit point partway up the side of the test chamber. The first 8 hours of operation were not affected by this leakage site but the final 16 hours were. Without this exit point, it is expected that the entire test chamber would have achieved rapid saturation and water flow would have been channelled forward and out of the chamber, but not necessarily along the shortest pathway. Another test conducted using floor inflow (Test 23 at 0.1 l/min) also experienced preferential water movement upwards within the clay block assembly before flowing horizontally forward and out of the test near the top of the assembly. These two tests demonstrate that the clay block assembly cannot be relied on to provide substantial resistance to erosion by inflowing water and that flow is a three-dimensional process that is difficult to predict.

Water content and density sampling was done in the course of dismantling this test. The data so generated support the observations and wetting patterns summarized above and provide some semi-quantitative information regarding quantities and regions where substantial material erosion occurred. Figure A-79 shows the water content distribution present at the time of decommissioning of this test. Of note is a region at the lowermost horizontal contact of the clay blocks and pellets shows a very high water content, likely associated with highly hydrated materials



Eroded channel and pipe exiting lower outside corner of test face

Section II at depth where inflow port and leakage site located: Extensive erosion of blocks at top righthand side

Gel-like remainder of block at top righthand side of assembly

Figure A-78. *Erosion features in Test 24 (enlargement of features shown in Figure A-78 at 0 and 0.6 m depth. Direction of water movement also shown using arrows).*

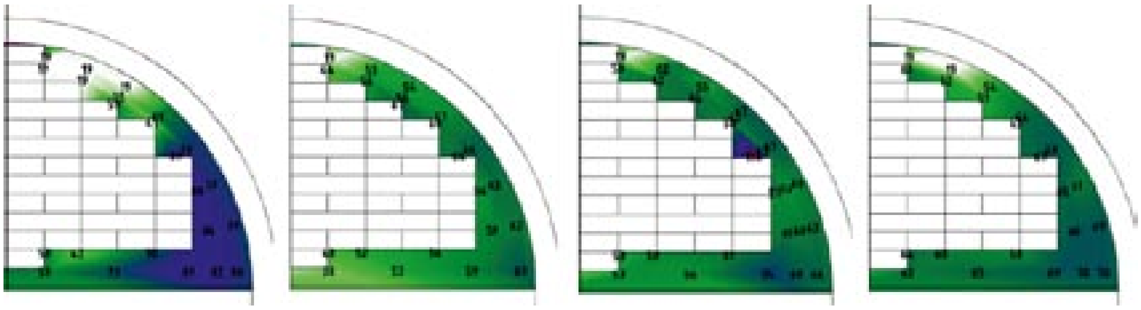


Figure A-79. *Water content data from Test 24.*

remaining close to the flow channel (Figure A-78), leading to the leakage point in the wall of the concrete tube. For the purposes of comparing the results of this test to other, less intensively sampled tests; the water content values associated with locations A-D shown in Figure 5-2 are provided in Table A-9.

A1.6 Test having water inflow of 1.0 l/min

A single test (Test # 5) was operated at a set water inflow rate of 1.0 l/min for a period of only 4.5 hours before being discontinued (inflow measured was actually 0.95 l/min). This test contained 1,169.4 kg of Friedland Clay Blocks and 475 kg of Cebogel pellets. Water was supplied via a single point source located at the mid-height and mid depth of the test assembly. Resistance to water inflow, wetting patterns and water outflow locations were all monitored. Several samples of pellet and block materials were recovered for water content and density analyses in the course of test dismantling.

Water outflow from the test cell was noted after only 8 minutes of system operation (8 litres inflow). This water volume represents less than 4% of the total and 7% of the air-filled void volume in the pellet fill. Erosion occurred in the course of this test but at this early stage of the study determination of erosion was not yet included in test operation. Subsequent tests saw improvements to the monitoring system and inclusion of erosion measurements.

Water first exited the lower, outermost corner of the test assembly where the floor, concrete tube and pellets intersected (Figure A-80) and this remained an important flow path for the 4.5 hours that this test operated. After an hour of test operation water was observed to begin exiting the test at the horizontal surface between the outermost column of clay blocks and the pellets. At four hours water also began to exit along the horizontal block-pellet interface surface from the next highest section in the assembly. Measurement of outflow from the test indicated that there was a reasonable stable rate of 0.47 l/min outflow from the test between 2 ¼ hours and 4.5 hours. This means that approximately 0.48 l/min was being retained by the test during this brief period. In the course of the test there was approximately 257 litres injected into the test and 104 litres exited, leaving 153 litres in the test chamber. The large voids present between the clay pellets in the original test set-up could have handled only 116 litres and there was still a visibly dry volume of pellets at the end of testing. The total porosity of the pellet fill (macropores and porespace within the pellets), was however approximately 255 litres. A quantity of water did enter the blocks but it would appear that most was taken into the pellets (Figure A-81). Figure A-81 shows the end-of-test wetting patterns observed during test dismantling and there is clearly a very high degree of system saturation achieved in the very short duration of the test. Rapidly inflowing water essentially fully flooded (except small region at crown) the back 0.9-m of the test chamber, including the region below the clay blocks. The water was then rapidly flowing forward to the outflow location (front face) where there was a less complete degree of saturation achieve. In order for so much water to have been taken into the system the clay pellets had to have acted in a manner similar to a gravel mass, providing essentially not resistance to inflow. With time the pellets began to swell and provide some resistance to advective flow, hence the incomplete saturation closer to the face of the test.

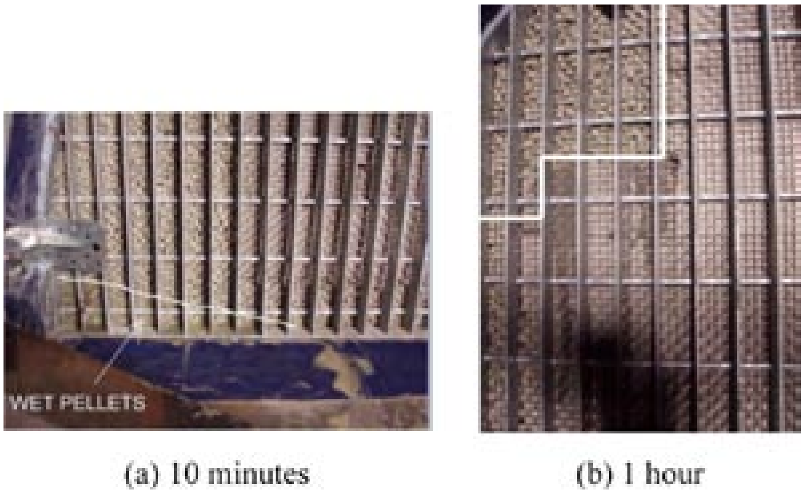


Figure A-80. *Outflow from Test 5 (showing initial outflow at outside corner and subsequent wetting up into pellet volume and outflow along horizontal block-pellet contacts).*

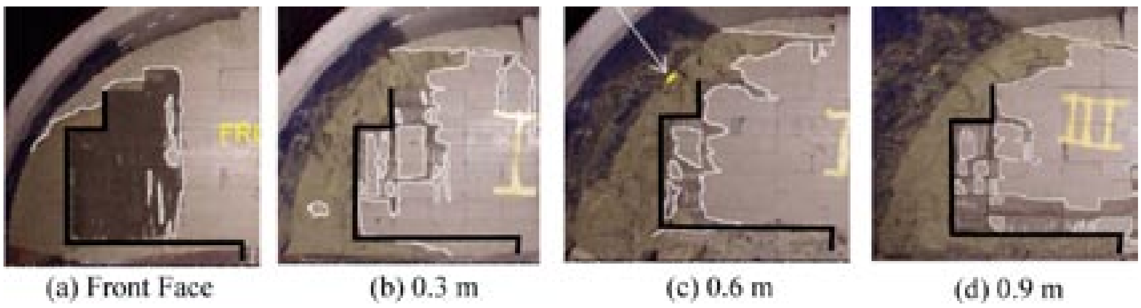


Figure A-81. *Wetting patterns in Test 5 (1.0 l/min for 4.5 hrs) (note extensive wetting of pellet fill excepting at crown of assembly and limited wetting of blocks due to rapid inflow and throughflow of water).*

Figure A-82 presents the resistance to inflow recorded for this test there was a very short-term development of resistance (45 kPa in less than 30 minutes) followed by a rapid decay to 15 kPa for the next half hour of operation. Beyond approximately 1 hour the resistance was gradually increasing again, reaching 30 kPa by the end of the test. The initial resistance is likely the result of the lack of any clear flow path through the system and the inflowing water's need to begin to develop a route into/through the test. Beyond 1 hour the system had begun to hydrate to a substantial level and so more consistent resistance to inflow was developing. The resistance to inflow was still effectively nil at 4.5 hours indicating that at this type of localized inflow the system will provide essentially no resistance to through flow and will need to be dealt with at the working face of the backfilling operations.

Erosion during the operation of this test was quite limited (perhaps 5,100 g), despite the considerable outflow volume. The material removed was a mixture of bentonite fines from the pellets and Friedland clay removed by flow along the pellet-block interface as well as down the front face of the test, as shown in Figure A-81 and Figure A-83. The test did not run long enough to develop any substantial erosional flow features.

Test 5 was only sparsely sampled in the course of disassembly and the results are provided in Table A-9. The water content measured during dismantling of the test ranged from 19 to 73%. These data and the visual records from the test show a test that indicate that rapidly flooded the majority of the macro pores of the pellet fill in the rear of the test cell. The pellet materials closest to the outflow face were not completely saturated but only a relatively small volume at the crown and below the blocks were still dry after only 5.5 hours of operation. This inflow rate is clearly well beyond the ability of a clay-pellet and clay block backfilling to accommodate or induce substantial delay in the through-flow of water. The entire pellet-filled volume will rapidly saturate and at about 6 hours after water first contacts the system, the outflow should approximately equal the inflow.

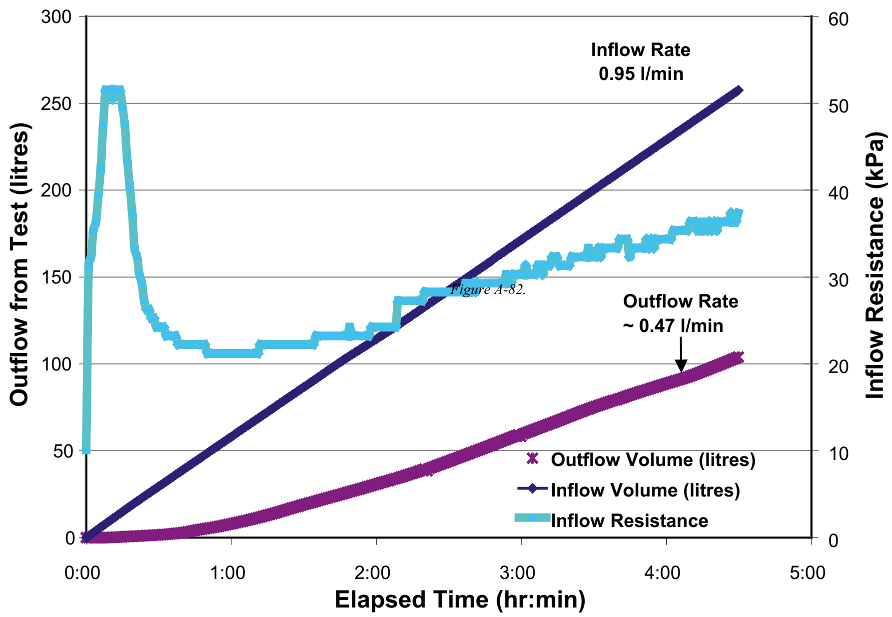


Figure A-82. *Inflow resistance and measured inflow/outflow for Test 5.*

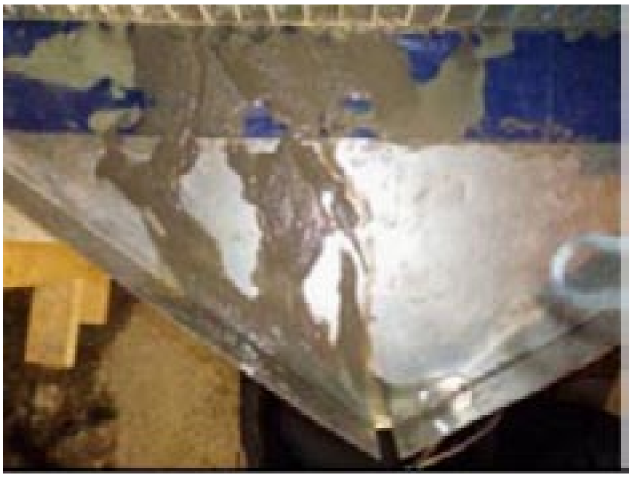


Figure A-83. *Material eroded from Test 5. (Dark material Friedland clay, light material pellet fines).*