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Hydraulic conductivity and specific storage of bentonite following prolonged thermal exposure

Minerals and Waste Programme

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Hydraulic conductivity and specific storage of bentonite following prolonged thermal exposure

J F Harrington and D J Noy

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Executive summary

The scope of this study was to determine the hydraulic properties of a specimen of bentonite which had previously been exposed to elevated temperatures during the Canister Retrieval Test (CRT) performed at the Äspö Hard Rock Laboratory. A series of well-constrained hydraulic measurements were performed on a specimen of compact bentonite, that had been situated close to the canister, yielded a mean hydraulic conductivity of 4.77×10^{-14} m/s (standard deviation = 0.49×10^{-14} m/s) using fluxes ranging from 1.6 to 4.6 µl/h and a mean specific storage coefficient for the same range of flux of 1.64×10^{-5} m^{-1} (standard deviation = 0.61×10^{-5} m^{-1}).

Data from this study are in close agreement with observations for unaltered saturated bentonite. Based on these observations, the BGS find no evidence for an adverse increase in hydraulic conductivity of bentonite as a result of its exposure to temperatures up about 80ºC for around 5 years.

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1 Introduction

The scope of the work described in this report was to determine the hydraulic properties of a specimen of bentonite which had previously been exposed to elevated temperatures in excess of 80 ºC for around 5 years. Testing was performed on a section of bentonite retrieved from ring 8 of the Canister Retrieval Test, CRT (Figure 1-1). Controlled flow-rate experiments were undertaken at the British Geological Survey (BGS) on an ascending and descending flow cycle with the specimen subject to a fixed backpressure. Head gradient was allowed to slowly evolve during each test stage i.e. a dependent variable simply related to the volumetric flow rate. Hydraulic conductivities were calculated from both steady-state pressure gradients and from analysis of the pressure transients. Transient analysis also yielded values for specific storage.

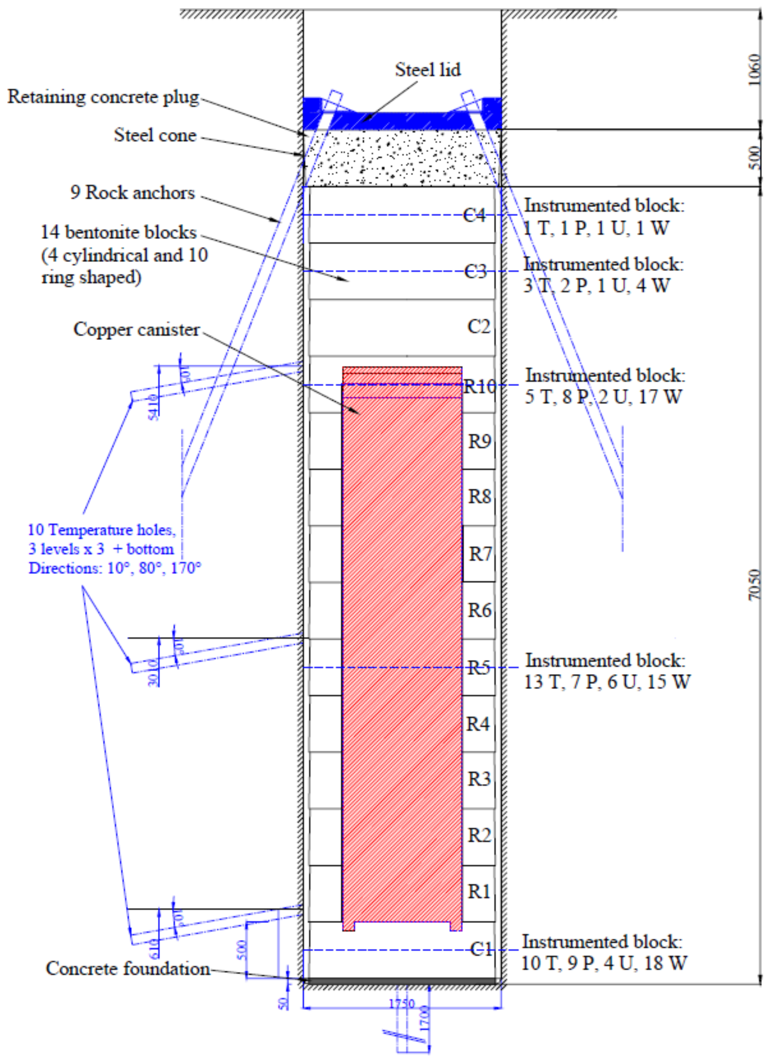

Figure 1-1 Schematic layout of the Canister Retrieval Test, CRT (Eng, 2008). Temperature (T), pressure (P), pore pressure (U) and relative humidity (W) sensors were located in five of the blocks. Outputs from these devices were used to track the state of hydration within the clay.

2 Experimental details

The BGS study was undertaken using a constant volume permeameter (Figure 2-1) which was designed and commissioned specifically for this experimental study. In this geometry the specimen is volumetrically constrained, preventing dilation of the clay in any direction. The apparatus consists of four main components: (1) a thick-walled dual-closure stainless steel pressure vessel, (2) a fluid injection system, (3) a backpressure system and (4) a data acquisition system operating within a LabView™ environment. Pressure in the injection and backpressure circuits is continuously monitored through independent pressure transducers providing high resolution data at low fluid pressures (<4.0 MPa). Testing was performed in an air-conditioned laboratory at a nominal air temperature of around 20ºC ±0.5 ºC.

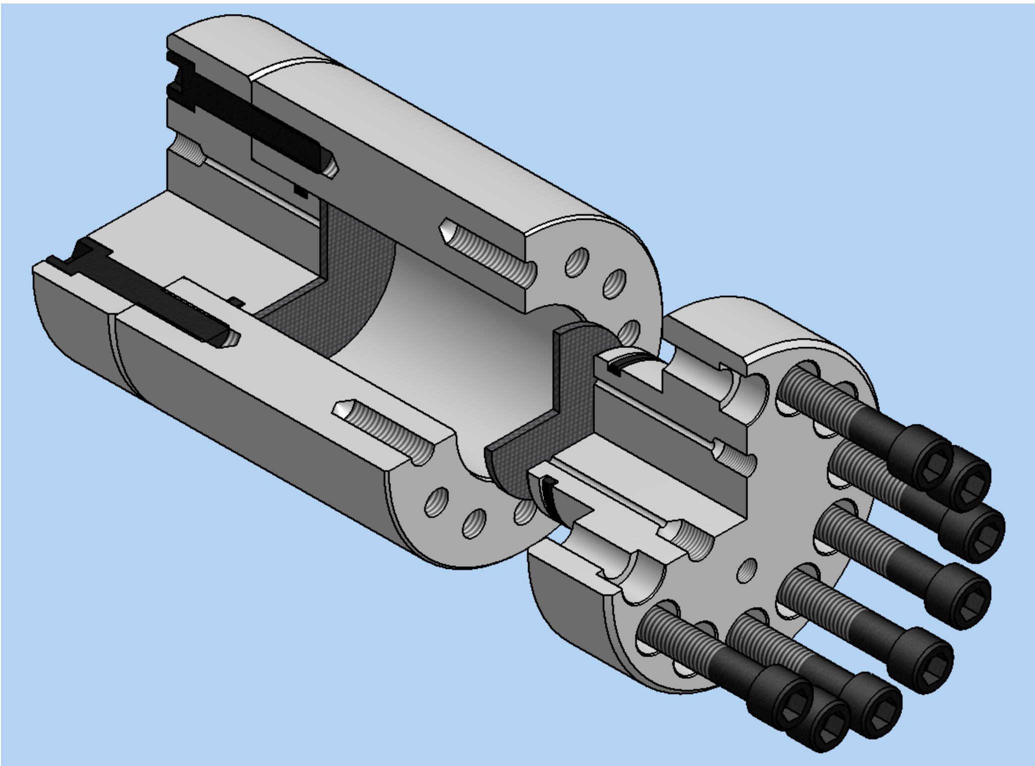

Figure 2-1 Cut-through isometric diagram of the test vessel showing the location of the injection and backpressure ports, position of sintered filters and location of cap screws. One end-closure is shown removed from of the bore of the vessel to illustrate individual system components.

The pressure vessel is comprised of a dual-closure tubular vessel manufactured from 316 stainless steel rated to 70 MPa. Each end-closure is secured by twelve high tensile steel cap screws which can also be used to apply a small pre-stress to the specimen if required. The 60 mm internal bore of the pressure vessel is honed to give a highly polished surface. Each end-closure has a dedicated port through which the pressure in each of the filters can be independently monitored.

Volumetric flow rates are controlled or monitored using a pair of high precision ISCO-100, Series DM, syringe pumps operated from a single digital control unit. The position of each pump piston is determined by a digital encoder with each step equivalent to a change in volume of 4.8 nano litres, yielding a flow accuracy of 0.5% of the set-point. Movement of the pump piston is controlled by a micro-processor which continuously monitors and adjusts the rate of rotation of the encoded disc using a DC-motor connected to the piston assembly via a geared worm drive. This allows each pump to operate in either constant pressure or constant flow modes. A programme written in LabVIEW™ elicits data from the pump at pre-set time intervals of 2 minutes.

Both ISCO syringe pumps were pressure calibrated to a known laboratory standard. Steps of 0.4 MPa in pressure were applied, with increments and decrements to quantify hysteresis. Using a spreadsheet, least-squares regression fits were calculated and the parameters used to correct the raw data.

2.1 SAMPLE PREPARATION AND PHYSICAL PROPERTIES

A block-sample of bentonite taken from the CRT was shipped to BGS (Figure 2-2). A cylindrical test specimen with diameter 59.87 mm and length 53.89 mm was manufactured by hand-trimming using a tubular former with a sharpened leading edge. The upper and lower surfaces were finished using a scraping action with a flat-bladed knife, leaving the end surfaces flat and parallel. The specimen was then carefully extruded from the former into the pressure vessel using a small hydraulic press.

Table 2-1 shows the basic physical properties of the sample at the time of preparation based on pre-test measurements of water content derived from off-cut material and an assumed specific gravity for the mineral solids. The prepared specimen was found to be slightly desaturated under atmospheric conditions (degree of saturation = 94.8%).

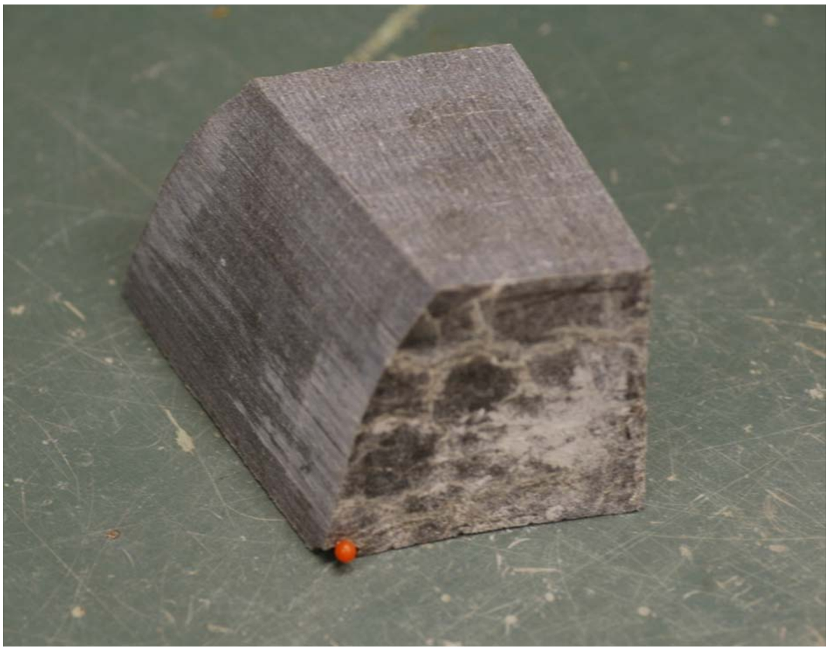

Figure 2-2 Photo of sample taken from block R8, direction 300º at a distance of 540 to 620mm from the centre (CRT R8:300:540-). The location of the orange pin indicates the surface closest to the canister. Photo courtesy of Clay Technology AB.

Table 2-1 Basic physical properties of the test specimen based on pre-test measurements of water content assuming an average specific gravity for the mineral phases of 2.77 $Mg.m^{-3}$.

Sample number	Sampling interval (code)	Water content (wt-%)	Bulk density ($Mg.m^{-3}$)	Dry density ($Mg.m^{-3}$)	Void ratio	Porosity	Degree of saturation
CRT-1	R8:300:540	24.8	2.00	1.61	0.726	0.421	0.948

2.2 EXPERIMENTAL HISTORY

The test comprises a sequence of steps (Tables 2-2). During an equilibrium (EQ) stage the specimen is backpressured with distilled water on both faces (i.e. zero hydraulic gradient). The purpose of this stage is to determine the hydration state of the sample by continuously monitoring the inflow of water from either end of the specimen. A controlled flow rate (CFR) stage is used to evaluate hydraulic conductivity and specific storage and involves the injection of distilled water into the specimen at a pre-defined volumetric flow rate shown in Table 2-2. Transient analysis of the pressure data provides an alternative determination of the hydraulic conductivity and specific storage. Distilled water was used as the backpressuring fluid in all hydraulic steps. The total test duration for test first cycle of water injection (including the EQ test stages) was 185.7 days.

Table 2-2 Summary of test steps showing stage numbers, type of stage (EQ = equilibration and CFR = controlled flow rate), injection flow rate and duration.

Step no.	Type	Flow rate (μl/h)	Duration (d)
0	EQ	-	13.9
1	CFR	1.6	27.0
2	CFR	2.6	23.8
3	CFR	3.0	20.0
4	CFR	4.6	15.9
5	CFR	2.6	34.4
6	CFR	1.6	16.7
7	EQ	-	34.0

3 Data reduction

Data were transferred to a spreadsheet for processing and plotting. Hydraulic transients were very well-defined and largely free of experimental noise.

The one-dimensional equation of flow is

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial x^2} \quad (1)$$

where S_s (m^{-1}) is the specific storage, K ($m.s^{-1}$) is the hydraulic conductivity, h (m) is the hydraulic head and x (m) is distance in the flow direction. This equation must be solved subject to the boundary conditions

$$q = \frac{Q}{A_s} = -K \frac{\partial h}{\partial x}\bigg|_{x=0} \quad (2)$$

and

$$h = 0 \text{ at } x = L_s \quad (3)$$

where q ($m.s^{-1}$) is the Darcy velocity, Q ($m^3.s^{-1}$) is the volumetric flow rate, A_s (m^2) and L_s (m) are the cross-sectional area and length of the specimen, respectively. Hydraulic head is related to the pore pressure, P (Pa), by

$$h = \frac{P}{\rho_w g} \quad (4)$$

where ρ_w ($kg.m^{-3}$) is the density of water and g (= 9.81 $m.s^{-2}$) is the acceleration due to gravity.

The head at x = 0 and flow at x = L_s as functions of time were obtained by numerically inverting the Laplace Transform solution given in Appendix 1. Five parameters are required to define the solution. Three are experimentally determined: Q, A_s, and L_s. The remaining two are the material properties that the test is designed to determine (i.e. K and S_s). In order to estimate the values of these parameters, a general nonlinear least squares fitting routine was used to minimise the differences between the calculated curves and the measured head data.

Hydraulic conductivity was also calculated from the head gradient at steady-state enabling the two values to be compared.

Permeability, k (m^2), was calculated from hydraulic conductivity using the relationship

$$k = \frac{K\eta_w}{\rho_w g} \quad (5)$$

where η_w is the viscosity of water (=0.001002 Pa.s).

4 Results

A series of well-constrained hydraulic measurements were undertaken by BGS on a specimen of compact bentonite taken from a location in close proximity to the canister from the CRT performed at the Äspö Hard Rock Laboratory.

During the initial equilibrium stage the sample rapidly hydrates, exhibiting a well defined transient leading to a near zero flow condition after 13.9 days. By the end of this stage the volumetric flow into the clay had reduced to an average flux of less than 0.1 μl/h, with a total 1.29 ml of water had been injected into the sample (Figure 4-1). This value is somewhat smaller than might be anticipated when compared to estimates of gas saturation based on the initial geotechnical measurements (Table 2-1). However, the discrepancy can be readily explained by compression of the residual gas phase when exposed to the backpressuring fluid.

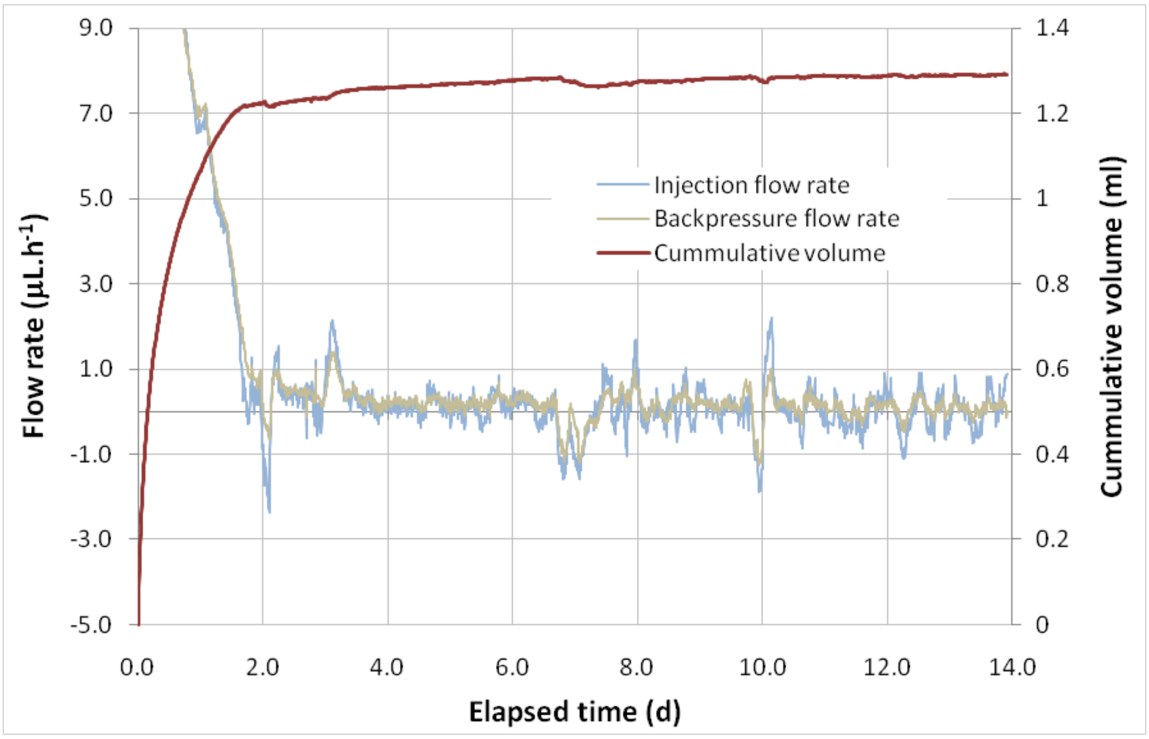

Figure 4-1 Flow into the specimen (monitored from either end of the core) during the initial EQ stage. Positive flow represent uptake of distilled water by the specimen. Inspection of the data shows near equal uptake of fluid from either end of the specimen, indicative of a homogenous sample.

Table 4-1 shows steady-state values for flow in and out of the specimen as well as injection and backpressure pressures for each stage of hydraulic testing (Figure 4-2). The small discrepancy between fluxes relates to minor leakage (≤0.3 μl/h) from one of the test systems. To accommodate this, hydraulic properties for specimen CRT-1 have been calculated for both inflow and outflow data (Table 4-2). Transient analysis of the pressure data has been undertaken in a similar manner yielding a second estimate for conductivity and an indication for the specific storage of the sample (Table 4-3, Figure 4-3). Examination of the conductivity data shows little variation in values between the data processing methods indicative of the quality of the raw data and the good mass balanced obtained during hydraulic testing.

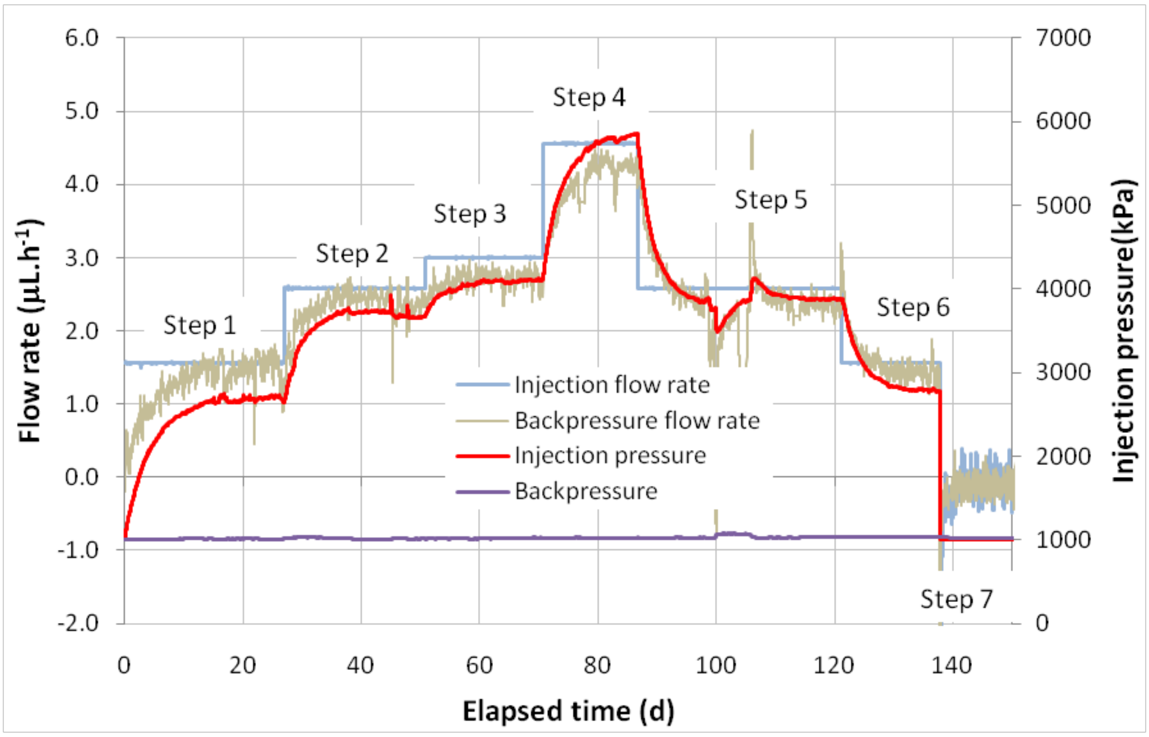

Figure 4-2 Flow and pressure data for test stages 1 to 7. Inspection of the data shows well-defined transients leading to steady-state conditions. Discrete spikes in data relate to small temperature fluctuations within the laboratory. Problems with the air conditioning system between 100 to 107 days resulted in a considerable noise within the data. However, projection of the flux and pressure asymptotes prior to this event suggests it had no long term deleterious effect on the data.

Table 4-1 Flow in and out, injection and backpressure and head gradient for each test stage of sample CRT-1 at steady-state. Inspection of the data indicates a good mass balance between flow in and out with difference less than or equal to 0.3µl/h.

Step no.	Flow in (µl/h)	Flow out (µl/h)	Injection pressure (MPa)	Backpressure (MPa)	Head gradient (m/m)
1	1.6	1.5	2.70	1.01	3193
2	2.6	2.4	3.67	1.01	5018
3	3.0	2.7	4.11	1.02	5808
4	4.6	4.3	5.83	1.02	9085
5	2.6	2.3	3.88	1.03	5413
6	1.6	1.4	2.79	1.03	3349

For fluxes in the range 1.6 to 4.6 µl/h, the mean hydraulic conductivity (based on all data) is 4.77×10^{-14} m/s (standard deviation = 0.49×10^{-14} m/s). The mean specific storage (S_s) for the same range of flux is 1.64×10^{-5} m^{-1} (standard deviation = 0.61×10^{-5} m^{-1}).

A cross plot of flow rate against head gradient (Figure 4-4) shows only minor hysteresis between increasing and decreasing flow cycles. While controlled flow rates were varied from 1.6 to 4.6 µl/h, values for head gradient (a dependent variable in this study) ranged from 3193 m/m (at the lowest flow) to 9085 m/m (at the highest). Linear regression of the data in Figure 4-4 yields threshold values close to zero indicating the bentonite exhibits little if any significant threshold (i.e. non-Darcian behaviour) to hydraulic flow. This observation is supported by recent work by *Villar and Gomez-Espina* (2009) who undertook a series of hydraulic and hydromechanical tests for a range of clay densities at varying temperature. Their results, for clays with similar dry density, yielded only one test where flow was not detected.

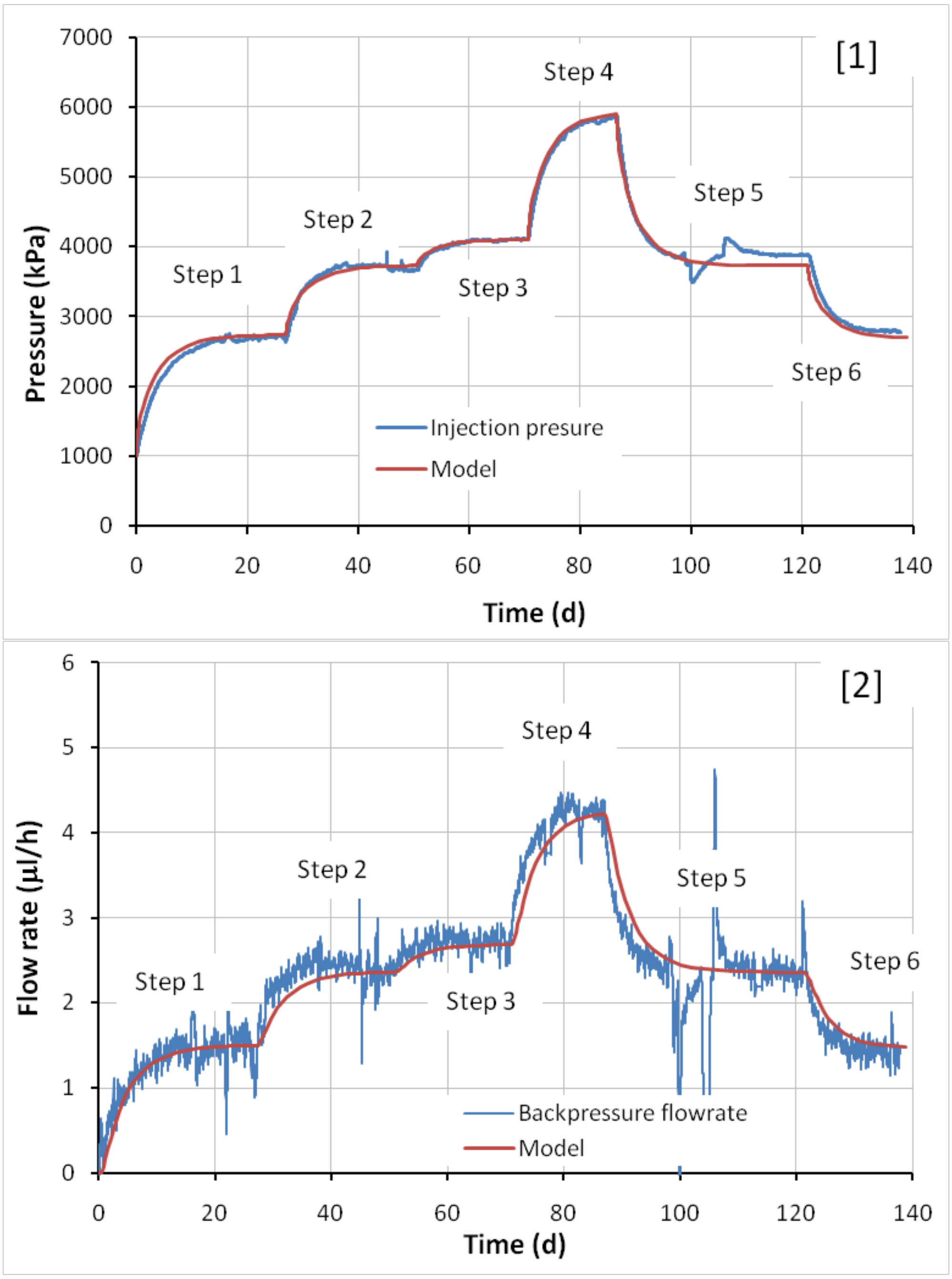

Figure 4-3 Analysis of hydraulic transients for CRT-1 based on backpressure flow rates. Plot [1] yields a good fit between predicted and measured pressures. In plot [2] there is a fairly good correlation between predicted and measured flux though some of the detail of the transients are less well-represented by the model. To improve model fits, data from test stages were individually fitted using an automated least-squares procedure optimised against the injection pressure (presented in Table 4-3).

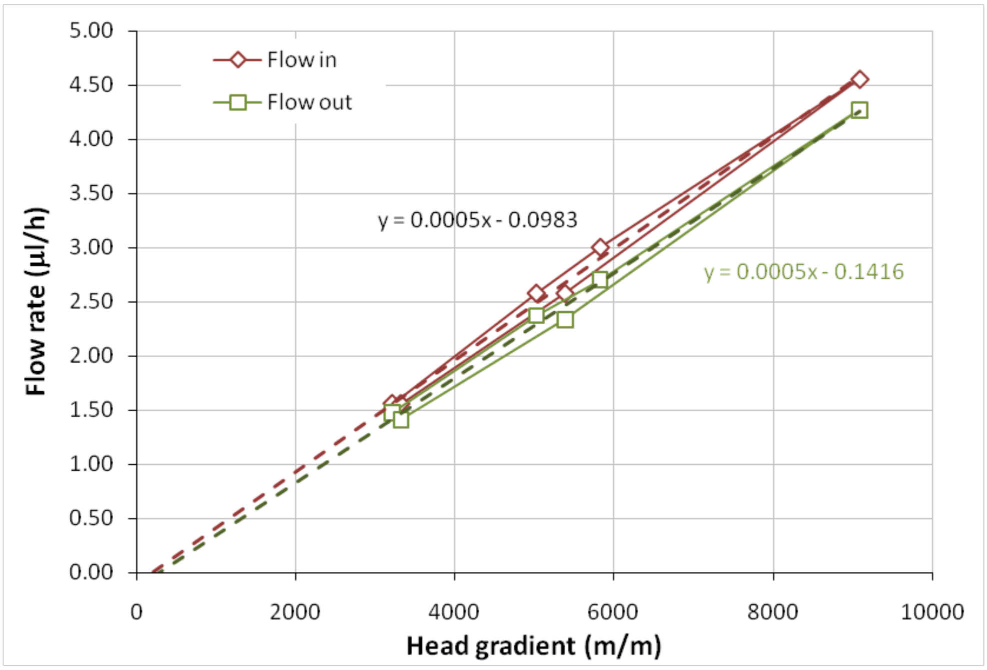

Figure 4-4 Flow in and out of the specimen plotted against head gradient. A small amount of hysteresis in the flow response between advancing and decreasing flow rates is observed in the data. Extrapolation of the results towards the y axis indicates no significant threshold (i.e. non-Darcian behaviour) to flow.

Table 4-2 Hydraulic properties for CRT-1 based on steady-state analysis of the data, showing hydraulic conductivity and permeability values for each test stage.

Stage no.	Hydraulic conductivity $K/10^{14}$ (m/s)		Hydraulic permeability $k/10^{21}$ (m^2)	
	Flow in	Flow out	Flow in	Flow out
Step 1	4.83	4.57	4.93	4.67
Step 2	5.07	4.67	5.18	4.76
Step 3	5.10	4.59	5.21	4.69
Step 4	4.95	4.64	5.05	4.74
Step 5	4.70	4.26	4.80	4.34
Step 6	4.60	4.16	4.69	4.24

Table 4-3 Hydraulic properties for CRT-1 based on transient analysis of the pressure data, showing hydraulic conductivity and specific storage values for each injection and backpressure flow rate.

Models based on injection flow rate						
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Conductivity (m/s)	4.73E-14	5.09E-14	6.53E-14	4.51E-14	5.22E-14	4.65E-14
Storage (m^{-1})	1.94E-05	1.29E-05	3.15E-05	1.37E-05	1.25E-05	1.44E-05
Models based on backpressure flow rate						
Conductivity (m/s)	4.54E-14	4.29E-14	5.05E-14	4.58E-14	5.04E-14	4.09E-14
Storage (m^{-1})	1.86E-05	1.13E-05	2.45E-05	1.39E-05	1.19E-05	1.27E-05

5 Discussion

It has been suggested that bentonite which has been subjected to sustained thermal exposure will exhibit a significant and permanent increase in hydraulic conductivity and that this observation has been overlooked by previous researchers because of the large flow gradients applied to the specimens in order to observe a measureable flow. Recent work by *Pusch et al.* (2010) quote two values for conductivity based on laboratory tests performed on bentonite specimens sub-sampled from the same R8 block (from the CRT) that was used in this study. While they provide no detail regarding test methodology, which is simply described as 'oedometer testing', the authors quote values for hydraulic conductivity of 2.0 $x10^{-11}$ m/s for both samples.

In the test geometry reported here, this hydraulic conductivity would yield a volumetric flow rate of 8 μl/h at a modest head gradient of 40m/m. Since the head gradient is a dependent variable in the BGS methodology, it was decided to inject distilled water at a flow rate of only 1.6 μl/h in order to minimise any perturbation of the system and avoid the potential movement of dissociated mineral components (if any exist). If the bentonite sample actually exhibited a conductivity of 2.0 $x10^{-11}$ m/s then this would generate a head gradient of only 8 m/m.

During step 1 of the test, the head gradient was allowed to independently evolve for 27 days. This allows water to flow through the test specimen at the lowest possible gradient. The data presented in Section 4 clearly shows a well-defined transient response leading to a conspicuous steady-state where flux in and out are closely matched. However, the pressure gradient required to achieve this flow was in excess of 3000 m/m and not the 8 m/m as predicted, yielding an average hydraulic conductivity of 4.7 $x10^{-14}$ m/s.

While this value is in close agreement with those previously reported for 'unaltered' saturated bentonite (*Harrington and Horseman,* 2003; *Dueck et al.* 2010), it is nearly three orders of magnitude smaller than those reported by *Pusch et al.* (2010). Subsequent increments and decrements in flow applied to sample CRT-1, again with the head gradient allowed to independently evolve, yield similar values for hydraulic conductivity.

Based on these observations, the BGS find no evidence for an adverse increase in hydraulic conductivity of bentonite.

6 Conclusions

It has been suggested that bentonite that has been subjected to sustained thermal exposure will exhibit a significant and permanent increase in hydraulic conductivity. To examine this issue, BGS undertook a series of well-constrained hydraulic measurements on a specimen of compact bentonite taken from the CRT performed at the Äspö Hard Rock Laboratory.

Specific attention was paid to the choice of test technique to minimise the head gradient applied to the specimen during each test stage. In total six constant flow rate tests were performed with flow rates ranging from 1.6 to 4.6 μl/h. The duration of each test stage ranged from 14 to 34 days, with the data exhibiting well-defined transient and steady-state behaviour.

Analysis of the data yielded a mean hydraulic conductivity of 4.77×10^{-14} m/s with a standard deviation of 0.49×10^{-14} m/s. The mean specific storage coefficient for the same range of flux was 1.64×10^{-5} m^{-1} with a standard deviation of 0.61×10^{-5} m^{-1}.

In contrast to recently reported values from *Pusch et al.* (2010), the data from this study is in close agreement with observations for unaltered saturated bentonite. It is important to note that if the permeability of the bentonite had indeed increased by three orders of magnitude following thermal exposure, then the application of these small volumetric fluxes would have resulted in the generation of head gradients ranging from 8 to 23 m/m.

However, this is clearly not the case and based on these observations, the BGS find no evidence for an adverse increase in hydraulic conductivity of the bentonite following its exposure to prolonged thermal gradients.

Appendix 1 Calculation of hydraulic parameters from flow transients

Consider a specimen of length L_s and cross-sectional area A_s with hydraulic head initially everywhere at zero. A fluid flow of Q is initiated at t = 0 into the specimen at the end x = 0 and the response of the hydraulic head at x = 0 is sought as a function of time.

The equation of one-dimensional flow is given by

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial x^2} \tag{A-1}$$

where S_s is the specific storage, K is the hydraulic conductivity, and h is the hydraulic head. This equation must be solved subject to the boundary conditions

$$q = \frac{Q}{A_s} = -K \left.\frac{\partial h}{\partial x}\right|_{x=0} \tag{A-2}$$

and

$$h = 0 \text{ at } x = L_s \tag{A-3}$$

To obtain the solution to (A-1), we take its Laplace Transform

$$p S_s \bar{h} = K \frac{\partial^2 \bar{h}}{\partial x^2} \tag{A-4}$$

where p is the transform parameter and $\bar{h}$ is the Laplace Transform of the head. The solution to this may be written as

$$\bar{h}(x) = A e^{(\lambda x)} + B e^{(-\lambda x)} \tag{A-5}$$

where A and B are constants to be determined from the boundary conditions and

$$\lambda = \sqrt{\frac{p S_s}{K}} \tag{A-6}$$

From the boundary condition in (A-3), we have

$$A e^{(\lambda L)} + B e^{(-\lambda L)} = 0 \tag{A-7}$$

Taking the Laplace Transform of (A-2), we have

$$A\lambda - B\lambda = -\left(\frac{q}{K}\right)\frac{1}{p} \tag{A-8}$$

Substituting using (A-7) and re-arranging, we have

$$A = -\left(\frac{q}{K\lambda}\right)\frac{1}{p}\frac{e^{(-\lambda L)}}{\left(e^{(\lambda L)} + e^{(-\lambda L)}\right)} \tag{A-9}$$

and

$$B = \left(\frac{q}{K\lambda}\right)\frac{1}{p}\frac{e^{(\lambda L)}}{\left(e^{(\lambda L)} + e^{(-\lambda L)}\right)} \tag{A-10}$$

Thus we may write the Laplace Transform of the head at x = 0 as

$$\bar{h}(x=0) = \frac{q}{Kp\lambda}\tanh(\lambda L_s) \qquad \text{(A-11)}$$

Similarly, we may write the Laplace Transform of the flow at $x = L_s$ as

(A-12)

The head at $x = 0$ and flow at $x = L_s$ as functions of time are obtained by numerically inverting the Laplace Transform solutions given in Equations A-11 and A-12 using the method of Talbot (1979). Five parameters are required to define the solution. Three are experimentally determined: Q, A_s and L_s. The remaining two are the material properties that the test is designed to determine (i.e. K and S_s). In order to estimate the values of these parameters, a general nonlinear least squares fitting routine was used to minimise the differences between the calculated curves and the measured head data.

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