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A novel centrifuge permeameter to characterize flow through low permeability strata

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ABSTRACT: A novel centrifuge permeameter (CP) system was designed to characterize and model seepage and reactive solute transport through low permeability materials and geological strata. A new CP module for the Broadbent G18 geotechnical centrifuge (2.0 m diameter), provides new capability for hydraulic conductivity (K) and transport testing of materials including drill cores, mine tailings and engineered barriers. By designing centrifuge models that maintain chemical equilibrium, reactive transport of solutes can be assessed within a reasonable experiment time at accelerated gravity. The K of minimally disturbed drill cores or porous materials having a diameter of 65-100 mm and a length of 20-200 mm can be measured using steady state flow, with a K detection limit currently within the order of 10^{-12} m/s. This paper presents K values as a function of depth below ground for drill core, and K as a function of effective porosity of reconstituted silica flour specimens.

1 INTRODUCTION

Low permeability clays, sediments and rocks can form natural hydraulic barriers known as aquitards in sedimentary sequences. Aquitards often overlie aquifers that yield strategically important fresh water resources, and form important cap-rocks or seals between shallow aquifers and deeper strata that are targeted for depressurization during gas or mineral extraction (Timms et al. 2012).

Measurement of the hydraulic properties of aquitards materials can be difficult and time consuming. Aquitards are defined as strata that exhibit a hydraulic conductivity K less than 10^{-8} m/s (Neuzil 1994). By comparison, low permeability clay barriers for hazardous waste landfills require K of $<10^{-9}$ m/s (US EPA 1989). Groundwater studies generally assume that aquitards are saturated, although semi-saturated aquitards may also form an effective barrier for seepage and migration of contaminants.

Centrifuge permeameter techniques have been developed over the past decade enabling flow and contaminant transport studies of aquitard materials that would otherwise not be possible, or studies that would take significantly longer by conventional techniques (Nimmo and Mello 1991, Conca and Wright 1998; McCartney and Zornberg 2005; Timms and Hendry 2008).

This paper reports a new centrifuge permeameter module designed for a Broadbent GT-18 geotechnical centrifuge (2.0 m diameter, 875 revolutions per minute, RPM). The new module was designed to test the K of porous samples by the National Centre for Groundwater Research and Training (NCGRT) at the University of New South Wales (UNSW).

The NCGRT geocentrifuge system is moderately sized and relatively economic to operate, whilst sufficiently large to minimize the G-level gradient across a core sample and enable real-time measurement of various parameters during flight. The geocentrifuge tests reported herein focus on hydraulic characterization of intact drill core samples, in contrast to the more common application of geocentrifuges for physical modelling of earth systems, and geotechnics (Taylor, 1995). As such, hydraulic characterization experiments in this geocentrifuge system use identical material and fluid properties to in-situ, or prototype systems.

All the K values reported here are vertical matrix values for intact cores that are assumed to be saturated. Hydraulic equilibrium occurs more rapidly in fine grained porous matrix at accelerated gravity compared with traditional methods (ASTM D7664). Matrix K values are an essential step in assessing bulk K at site and basin scale that may also be a function of heterogeneity, fractures and faults.

2 GEOCENTRIFUGE SYSTEM

2.1 *Geocentrifuge models*

The NCGRT centrifuge (Figure 1, Table 1) is a Broadbent Modular Geotechnical Centrifuge with a

geotechnical beam GMB GT6/0.75F (2 × 10.8 kg strong box sample at 300 G-max) and a new centrifuge permeameter GMP GT2/0.65F (2 × 4.7 kg permeameter sample at 556 G-max). A 22kW motor drives a variable speed of 10 to 875 RPM. The centrifuge permeameter (CP) module was designed specifically for groundwater research, although the rotary unions and geotechnical beam module are standard, and a standard drum module can also be fitted to this centrifuge.

Table 1. Specifications and performance details of the Broadbent G18 centrifuge permeameter (CP) system (Broadbent, 2011).

Dimensions/mass	
Diameter (lower rotary stack)	200.0 cm
Radius to top sample chamber	45.0 cm*
Radius to base sample chamber	65.0 cm**
Total mass	4800 kg
Performance	
Rotational speed	10 – 875 RPM
Maximum sample length	20.0 cm
Maximum sample diameter	10.0 cm
Maximum sample mass	4.7 kg
Maximum sample density	SG 3.0
Maximum influent reservoir capacity	n/a***
Maximum effluent reservoir capacity	1000 mL
Maximum payload	18.11 kg

* 385 G at 875 RPM; ** 556 G at 875 RPM; *** 471 G at 875 RPM; *** Influent is fed via a peristaltic pump from an external reservoir.

This paper describes the first application of this CP, a relatively large module that allows on-board instrumentation and real-time monitoring of a range of parameters. Since a maximum G-level of 471 applies at the centre of the sample weight, the rating of the centrifuge permeameter is 2.2 G-ton (471×4.7/1000). The total weight of two permeameters when empty is 12.4 kg plus an allowance of 1.0 kg of effluent in the reservoir. A large cross-sectional flow area (100 mm diameter), low volume influent pumps and a custom made effluent suction extraction system have enabled routine testing of low permeability matrix.

2.2 *Permeameter flow systems and instrumentation*

A low flow rotary union with a capacity of 0.1 to100 mL/minute connects the influent lines A and B to permeameters 1 and 2 without cross flow. Unlike UFA centrifuge systems, however, this flow union is not sealed, so the maximum head of water within this centrifuge is the radial distance from the rotary union to the top of the sample. Influent is fed from a pair of burettes via a pair of custom designed low flow rate peristaltic pumps mounted to the outside the centrifuge.

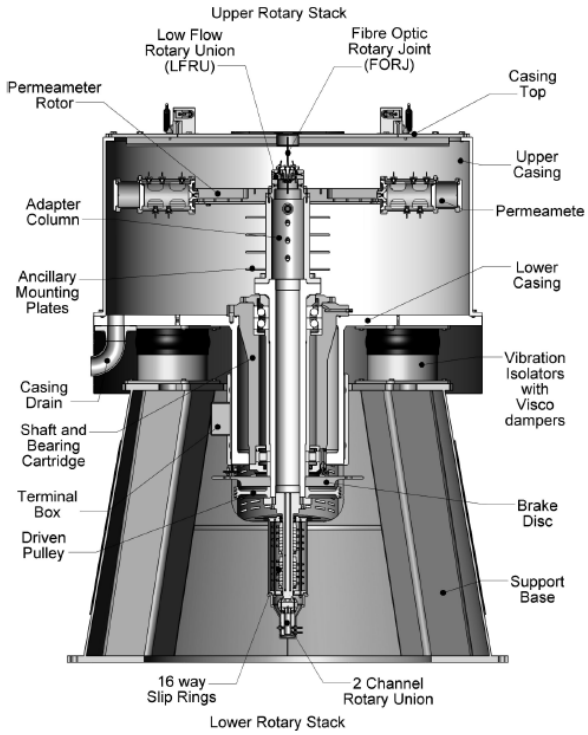

Figure 1. Section of the Broadbent G18 centrifuge fitted with CP module (Broadbent, 2011).

The influent pumping and monitoring systems are connected to a PC via a Fiber Optic Rotary Joint (FORJ) and controlled using LabVIEW software. The system is configured to maintain a constant head of influent above the sample.

Each permeameter assembly (see Figure 2) employs a pair of custom designed carbon fibre rod electrical conductivity (EC) electrodes to detect the influent reservoir height. The electrodes protrude through a pluviator cap into the influent reservoir and when the reservoir is depleted a decrease in EC is detected and transmitted back to the PC. The corresponding peristaltic pump is then switched on to automatically resupply the reservoir. Carbon fibre rod (1 mm diameter) was selected as the electrode material due to its high tensile strength, low mass, high electrical conductivity and good resistance to corrosion.

Effluent flows from the porous sample through a drainage plate and into the effluent reservoir. Effluent is extracted via a syringe or peristaltic pump through a 'U' shaped tube that connects to the base of the effluent reservoir (Figure 2b). This system enables samples to be extracted without the need for the permeameters to be taken off the beam. An air vent maintains a zero pressure outflow boundary.

As shown in Figure 2, a coordinate z is defined as positive from the base of the porous sample toward the central axis of rotation, using the convention for analysis of 1-g column tests (Dell'Avanzi et al. 2004). The permeameter has an outlet face at a radius r_0 (Zornberg and McCartney, 2010).

$$z = r_0 - r \tag{1}$$

The value of $N_{r,mid}$ at mid height of the sample is $z = L/2$ where L is the length of the sample. The length of the sample is typically less than the length of the sample chamber. The $N_{r,mid}$ is also known as the G-level, providing a single representative value of N_r. This does not imply that the G-level is constant through the specimen.

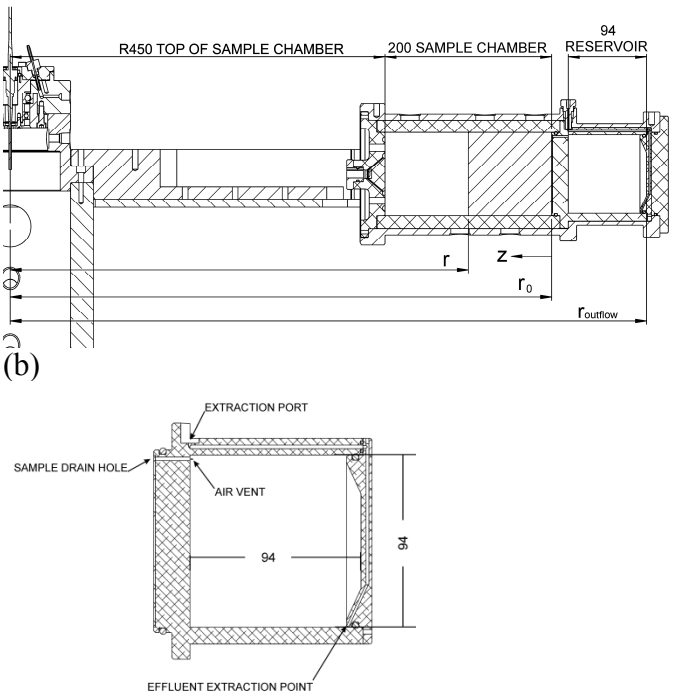

Figure 2. Cross section of the (a) centrifuge permeameter and beam showing new reservoir and reference points and (b) detail of new reservoir liner with suction extraction port.

2.3 *Hydraulic conductivity calculations*

Using Darcy's Law (Equation 2), the discharge velocity (v) during laminar flow of water through a porous media can be calculated as a function of the gradient in hydraulic head, and a constant of proportionality referred to as the hydraulic conductivity (K):

$$v = -K\frac{\partial h}{\partial L} \tag{2}$$

where h is hydraulic head (i.e., the sum of the pressure head and elevation head) and L is length.

The K of aquitards tested in the CP can be calculated for different infiltration rates v and centrifuge angular velocities ω using the version of Darcy's Law (Zornberg and McCartney 2010):

$$K = \frac{-v}{\frac{\omega^2}{g}(r_o - z)} \tag{3}$$

The use of this equation is based on the key assumption that the pressure head is constant with depth during steady-state infiltration. This assumption was validated for compacted silt specimens by Zornberg and McCartney (2010). This assumption implies that water flow is primarily driven by the gradient in centrifuge elevation head. No scaling relationships are involved in the calculation of K, as the centrifuge acceleration term is incorporated into the centrifuge elevation head (Parks et al. 2012). Equation 3 can also be expressed in terms of revolutions per minute (RPM) as follows:

$$K = \frac{0.248Q}{A.r_m(RPM)^2} \tag{4}$$

where K is the hydraulic conductivity (m/s), Q is the fluid flux imposed by the flow control system (mL/h), A is the sample flow area (cm^2) and r is radial distance at the mid-point of the core sample (cm).

3 EXPERIMENTAL SETUP

3.1 *Core preparation*

Minimally disturbed clayey-silt drill core was obtained using a rotary drilling rig equipped with 'C' size Triefus triple core barrels (101 mm internal diameter ID). The coring system was designed with a cutting tip ahead of the PET lined core barrel to minimize exposure of the core to drilling fluids in the hole. The cores, contained within PET liners were transferred directly from the core barrels to portable 5ºC storage on site, and thence to a laboratory 5ºC storage, reducing the potential for moisture loss and desaturation. Clayey-silt drill cores were transferred directly into the permeameter liners using a custom designed core trimmer, with initial ponding of influent resulting in self-sealing of the cores in the liners.

Rock cores from deep sedimentary basins were obtained using rotary mud drilling methods, using standard coring methods (65-80 mm diameter), with cores stored in open air trays. These cores were resaturated with synthesized porewater as described in Section 3.2. Rock cores were set in the permeameter liners using resin (black RS Components 199-1430 resin and hardener mass ratio of 10.97:1). The resin was selected due to ultra-low permeability, fast curing rate and strong adherence to acrylic. Potting rings (ID 90 mm and length 30 mm, hard anodised aluminum alloy AL6061), custom designed by UNSW, were used to ensure that the resin set sample precisely matched the top and base of the core. Flat core surfaces and uniform cross-sectional area were assumed in K calculations. The UNSW potting rings were then fitted within the acrylic liner via double O

ring seals. Both clayey-silt cores and rock cores set in resin were connected to the CP drainage plate via a 1mm thick A14 Geofabrics Bidim geofabric filter (110 micron, and permeability of 33 m/s) laid on top of a Whatman 5 Qualitative filter paper.

3.2 *Influent preparation and core re-saturation*

Influent was obtained from piezometers at a similar depth to the core samples, or was synthesized with an ionic strength, Ca/Na ratio and pH that approximated in-situ pore water chemistry. Natural influent sampled from piezometers was preferred to ensure realistic conditions, but was not possible for the shale samples because they were drilled from deep sedimentary basins.

Saturation of cores for K testing was ensured by preservation of drill core and vacuum plate saturation, and verified by monitoring weight changes during testing, and moisture tests before and after testing. A custom vacuum plate device was designed by UNSW to fit the CP liners containing the cores, drawing ponded influent from the top to the base of the cores. After 12-48 hours, or upon effluent flow from the base, the liners were then transferred directly to the CP module without disturbing the sample.

3.3 *Silica flour porous matrix*

A synthetic aquitard, or non-reactive low permeability porous matrix was prepared in the column with silica flour. Two sizes of silica flour were used, 75 µm diameter (95% passing 200 mesh) and 45 µm diameter (95% passing 350 mesh). The flour supplied by Wallarah Minerals Australia, and comprised 99.0% silica, 0.03% Fe_2O_3, with 0.2% loss on ignition. In preliminary tests, the flour was packed in the column under wet conditions in 20 mm lifts, using a custom made Teflon hand compactor with a diameter to tightly fit the interior column. The top of each lift was scrapped prior to packing additional matrix. An alternative packing method, the silica flour was pre-mixed with RO purified water (170 mL per 700g of flour) and the slurry poured into the CP liner. The flour was then compacted at 10G with a head of water ponded.

3.4 *Deuterium tracer*

Deuterium (^2H) has a natural abundance in water of approximately 15576 mg/L. In this work, the influent solution was raised to 200% of the natural abundance of deuterium (31152 mg/L), by the addition of 3.12 mL/L of $^2H_20$ (99.8% concentration). Influent and effluent ^2H concentrations were then determined by measuring the $^1H/^2H$ ratio with a Los Gatos DLT100 isotope analyser. The breakthrough of the tracer was measured to within 0.1%.

4 RESULTS AND DISCUSSION

4.1 *K testing of drill core in the CP module*

K testing results are shown in Figure 3 for a semi-consolidated clayey-silt (100 mm diameter), from 26.0 m depth at the Cattle Lane site (NSW, Australia). The target G-level of 80 was determined by independent consolidation testing to ensure that total stress applied did not change the void ratio of the core. The apparent K is only considered a reliable measurement when the influent rate equals the effluent rate. The apparent K at steady was 3×10^{-9} m/s, based on <1 hour measurement intervals, and 9×10^{-10} m/s based on >12 hour measurements. The moisture content of this core was 66% before and after CP testing.

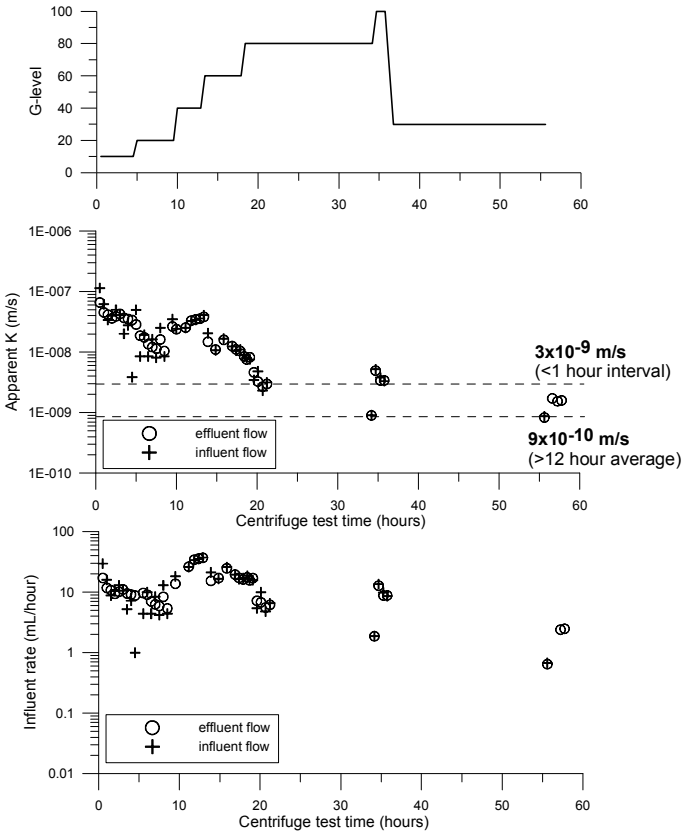

Figure 3. Flow rate and apparent hydraulic conductivity as a function of G-level for clayey-silt sediment, Cattle Lane site, 26.0 m depth, 100 mm diameter core.

K values as a function of depth below ground for all cores tested to date in the CP are summarized in Figure 4. The dataset includes semi-consolidated clayey silts from several undisclosed sites in Australia's Murray-Darling Basin and shale core from undisclosed sites in Eastern Australia. K values between 10^{-6} and $<10^{-12}$ m/s have been measured for a variety of geological strata.

Intact shale core were very low permeability as very high G-levels were required to force flow (up to 520 G). K ranged from $<10^{-12}$ to 4×10^{-10} m/s (n =12), compared with a resin only K of $<10^{-12}$ m/s. Of these

data, half the values were less than current detection limit of the instrumentation $<10^{-12}$ m/s (n = 6). K of shales tested to date were significantly less than for semi-consolidated clayey sediments overlying high yielding gravel aquifers.

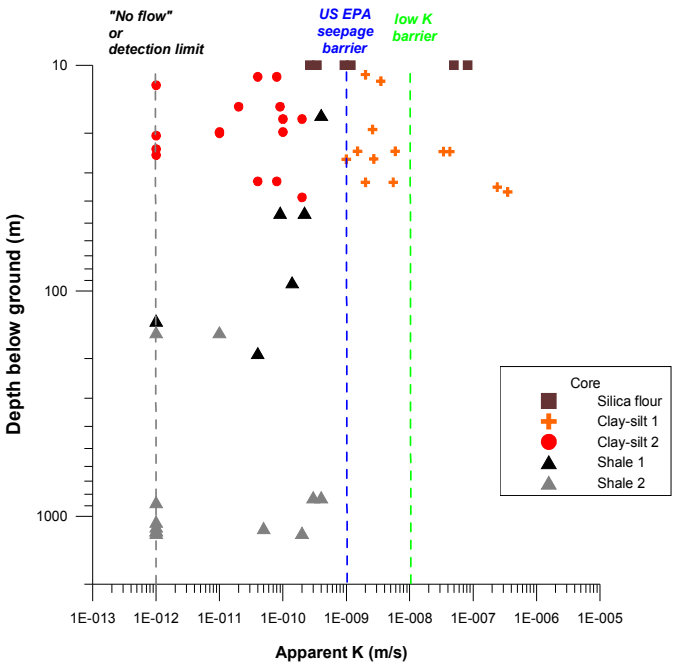

Figure 4. Hydraulic conductivity as a function of depth for silica flour, sediment and rock core samples , at steady state flow in the new centrifuge permeameter.

4.2 *Verification of K by independent testing*

The K results for the Cattle Lane core at 26.0 m depth was consistent with in-situ K measured by vertical pore pressure propagation (Timms and Acworth, 2005), but was significantly higher than blind constant head tests by an independent geotechnical laboratory. The in-situ K values were 1.6 to 4.0 $\times 10^{-9}$ m/s, compared to CP test results of 3×10^{-9} to 9×10^{-10} m/s and constant head K values of 1.5×10^{-10} and 4.9×10^{-11} m/s. The in-situ K value was measured over a vertical section from 15 to 35 m depth in the homogeneous clayey-silt deposit, while the constant head test was on similar core from 28.0 m depth. The constant head permeability methods (AS 1289 6.7.3, 5.1.1) used distilled water influent and a standard total stress of 50 kPa, irrespective of the core depth.

It was not possible to test very low permeability shale cores with standard techniques, as flow was not able to be induced Therefore, the successful steady state flow testing of shales at accelerated gravity has provided important information about these aquitards that was otherwise not possible to obtain.

4.3 *Solute transport experiments*

Preliminary solute transport experiments in the CP module with non-reactive matrix (silica flour) and non-reactive influent tracer (deuterium isotope) were designed with a G-level to achieve a flow rate between 0.5 to 1 mL/minute, irrespective of the low K matrix (Figure 5). The target flow rate enabled a reasonable definition of breakthrough curves with effluent sample volumes of 1-2 mL within several hours. The 45 micron silica was also tested in a benchtop column at a higher flow rate with a pressure pump. The K of 10^{-8} m/s indicated that the same silica flour was significantly lower (Table 2) at G-level 60 due to compression under the centrifuge acceleration field.

Table 2. Solute transport through silica flour.

Setting	Experiment 2		Experiment 3	
	P1	P2	P1	P2
d-95 (micron)	45	45	75	75
G-level	60	60	30	30
Flow* (mL/min)	0.4	0.6	1	0.8
$K\times^{-10}$(m/s)	2.7	3.2	12	9.3
Breakthrough				
Core volume (mLs)	254	254	195	162
Effluent volume (mLs)	157	169	62	46
Effective porosity	0.6	0.7	0.3	0.3
Time (hours)	6.8	7.3	8.5	9.9

* Steady state flow

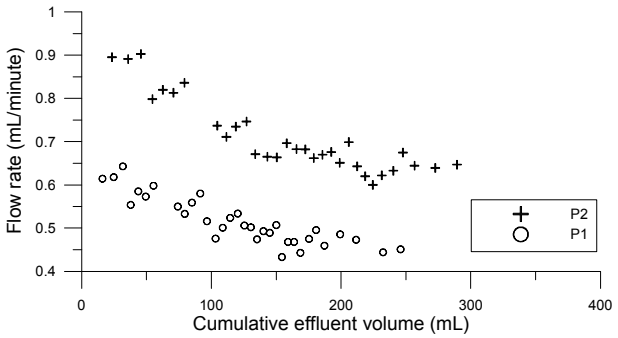

Figure 5. Flow rate versus cumulative effluent volume for 45 µm silica flour experiment 2(60*g*).

Selected experimental parameters including effective porosity and pore volumes are reported in Table 2. One pore volume was defined $C/C_0 = 0.5$, where C is effluent concentration and C_0 is influent concentration. The effective porosity of the matrix during the CP experiment was calculated by dividing the pore volume by the total volume of the silica matrix. The breakthrough curves in Figure 6 show that solute transport behavior was repeatable and that more dispersion occurred in Experiment 3 with the larger silica flour at a lower G-level. Contaminant transport experiments can now proceed in this system, provided that a stable porous medium and chemical equilibrium are maintained. An indicator of chemical equilibrium, the Damkohler number, as illustrated for geocentrifuge applications by Timms

et al. (2009), based on independently tested reaction times and measured flow contact time.

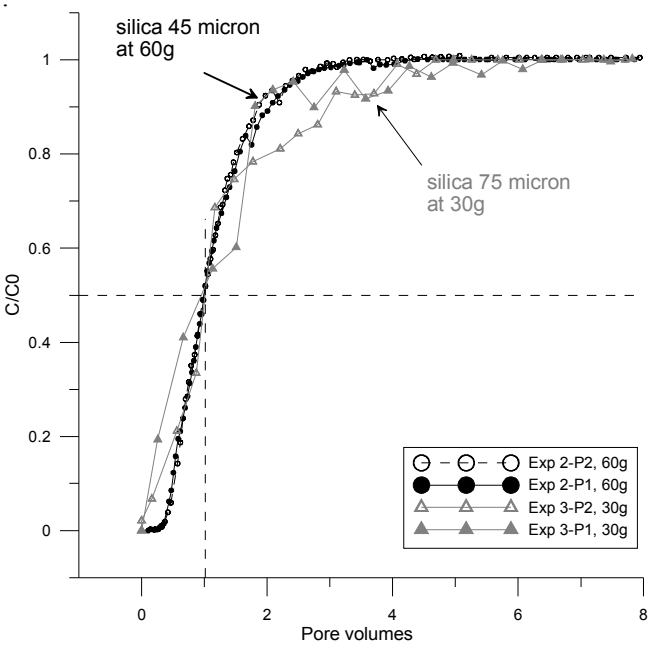

Figure 6. Breakthrough curves of non-reactive deuterium tracer through synthetic non-reactive aquitard materials (45 µm and 75 µm diameter silica flour at 60g and 30g respectively).

5 SUMMARY AND FURTHER WORK

The new CP module enables K testing of low permeability geological material for various applications, including measurements that would otherwise not be possible. Instrumentation developments that are currently in progress will enable real time monitoring of several parameters including moisture content. Current research includes evaluating the affect different influent chemical compositions have on the hydraulic properties of different materials, and reactive contaminant modeling for pore water seepage that may occur over hundreds to thousands of years.

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7 ACKNOWLEDGEMENTS

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