1 **Measuring And Predicting Transport in Composite Cementitious Barriers**

2

3   by

4   Dr Peter A Claisse (corresponding) and Dr Esmaiel Ganjian,

5   School of Science and The Environment, Coventry University, Priory Street, Coventry, CV1 5FB

6   UK. phone:+44 24 7688 8881, fax: +44 24 7688 8296, email: p.claisse@coventry.ac.uk

7   and

8   Professor Alan Atkinson and Dr Mark Tyrer,

9   Department of Materials, Imperial College, Prince Consort Road, London, SW72BP, UK

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13   **Peter Claisse** is a Reader in construction materials at Coventry University where he has been

14   working since 1992. Previously he spent many years as a site Engineer and in commercial research

15   for the nuclear industry. He is a member of ACI committee 236, Material Science of Concrete. His

16   main research interests relate to the use of recycled materials in concrete and the transport

17   properties and durability of concrete.

18

19   **Essie Ganjian** has been a post-doctoral research fellow at Coventry University since the 1998. His

20   speciality is in Civil Engineering materials and he has been involved in research in measuring and

21   modelling the thermal conductivity of concrete, use of by-products such as sulphur, natural

22   pozzolans and Silica Fume in concrete and also use of mineral waste in cementitious materials.

23

24   **Alan Atkinson** has been Professor of Materials Science at Imperial College of Science, Technology

25   and Medicine, London since 1995. Previously he was head of materials chemistry at AEA

26   technology, Harwell laboratory, with responsibility for applied research on Engineered Barriers in

27   Waste Disposal.

28

29   **Mark Tyrer** has been a post-doctoral research fellow in geomaterials at Imperial College since

30   1995. Previously he had extensive experience in industry and academia on research into waste

31   containment and aquifer protection.

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Abstract.

Concrete barriers are being designed as alternatives to conventional systems used as landfill liners. The concretes are made from mineral wastes and are expected to be cheaper and more effective than current systems. In order to predict the performance of the barriers transport modelling is used. The processes of advection, diffusion and adsorption are included in the model. Laboratory experiments have been carried out to determine the properties of the concrete mixes and large site trials have been carried out to test the model using the material parameters obtained. Confidence limits for the results have been obtained by running the model with successive data sets representing extreme values of the input data. The observed results from the site trials generally fall within the expected limits but there are some notable exceptions. It is concluded that transport modelling of real landfills is not an exact science.

Introduction

Transport processes in concrete are of interest for the estimation of the durability of embedded steel in reinforced structures and for the prediction of the performance of concrete when used as a barrier to prevent migration of harmful species (1). This paper is concerned with the second of these. Interest in concrete as a barrier for lining landfills has arisen for the following reasons:

- Current liner technology based on high density polyethylene (HDPE) membranes and bentonite enhanced sand is expensive and its production and installation involves a high environmental impact.
- HDPE membranes are easily damaged after installation. A concrete barrier provides a relatively hard concrete surface to permit operation of vehicles and to prevent damage from large items of waste compacted onto it.
- The concretes which are used for these barriers are made from waste materials which would otherwise go into landfills.

This paper describes a programme in which transport properties were measured in the laboratory and used to predict the performance of site trials. The barrier used in the site trials had two layers of concrete with a layer of clay between them. This system was used to overcome problems with possible cracking of the concrete.   Four elements were studied: Na, K, Ca and S. These elements are not generally of concern in the environment but it was not possible to use toxic elements such as Hg because the work involved large quantities of leachate in field-scale trials.

Research Significance.

The research reported in this paper is currently being used by the UK waste industry as a basis for proposed landfills. The work forms part of a safety case which is being considered by the Environment Agency for the purpose of issuing licenses.

The Computer Model

A computer model has been written to simulate the transport processes. This model was used both to obtain transport properties from the laboratory results and to predict the results from the site trials. In each application the calculations are identical. The only differences are in the exact output given and the length of time that a run simulates. The model is based on physical transport processes (diffusion and advection) with linear adsorption and uses the following assumptions:

1. The following mechanisms are assumed not to be significant: Thermal migration, Electromigration, Osmosis, Electro-osmosis, Capillary suction.

2. The barrier is assumed to be saturated when the leachate first comes into contact with it.

3. The layers of the barrier are assumed to be homogeneous. In particular "boulders" are assumed not to form. These would be regions surrounded by impermeable layers of carbonates, chloroaluminates or magnesium compounds which do not contribute to the transport or adsorption.

4. The properties of the barrier are assumed not to change with time or the amount of transport that has taken place through it other than the gain or loss of ions due to the transport processes.

1   5. The adsorption processes are assumed to reach equilibrium within each time step.

2

3 **The Transport Processes**

4

5 *Advection*

6 In this process the pressure of the leachate head causes water flow which carries dissolved ions

7 through the barrier. The rate of transport through the barrier will be determined by the coefficient of

8 permeability k which has the units of m/s and is defined from equation 1 (2):

9

10    $$V = \frac{k(h_1 - h_2)}{x} \quad m/s \qquad\qquad [1]$$

11 where V is the Darcy velocity of the fluid flowing through a thickness x (m) with pressure heads h_1

12 and h_2 (m) on each side.

13

14 *Diffusion*

15 In this process the dissolved ions move through the water at a rate determined by the concentration

16 gradient. The flow per second per unit cross sectional area of a porous solid (the Flux, F) is given by

17 equation 2 (2).

18

19    $$F = \varepsilon D \frac{dC_l}{dx} \quad kg/m^2/s \qquad\qquad [2]$$

20 where ε is the porosity, D is the intrinsic diffusion coefficient and C_l is the ionic concentration in the

21 pore fluid.

22

23 *Adsorption*

24 The physical transport processes are restricted, in part, by adsorption in which a linear isotherm is

25 assumed, *i.e.* a fixed proportion of the ions in any part of the barrier are adsorbed onto the matrix

26 and will not move. To describe these processes two different ionic concentrations must be defined:

27

28 C_l kg/m^3 is the concentration of ions per unit volume of liquid in the pores. These ions will pass

29 through the barrier under the influence of the physical transport processes. The concentration per unit

30 volume of the solid will be εC_l where ε is the porosity.

31

1   C_s kg/m^3 is the total concentration (including adsorbed ions) per unit volume of the solid. The ions

2   which are adsorbed onto the solid will not move. The capacity factor is defined in equation 3 (3).

3

4    $$\alpha = \frac{C_s}{C_l}$$ [3]

5   Note that we may calculate $k = \dfrac{Concentration\ in\ solid}{Concentration\ in\ liquid} = \dfrac{Cs - \varepsilon Cl}{Cl} = \alpha - \varepsilon$ [4]

6

7

8   **Basis Of The Calculations:**

9

10

11   *Input data*

12

13   The barrier is constructed with up to three layers. Each layer is characterised with the following

14   parameters:

15

16   For layer j

17

18   Layer Thickness = x_j

19   Capacity factor = α_j

20   Permeability = k_j

21   Intrinsic Diffusion coefficient = D_j

22   Porosity = ε_j

23

24   Within the programme each layer is divided vertically into a large number of cells.

25

26   **Methods Of Calculation:**

27

28   *Darcy Velocity*

29

30   This is calculated as follows:

31

1 $$V = \frac{k \times \left(H + x_1 + x_2 + x_3 \right)}{x_1 + \left(\dfrac{x_2 \times k_1}{k_2} \right) + \left(\dfrac{x_3 \times k_1}{k_3} \right)} \qquad \ldots[5]$$

2

3 Where H is the head of leachate in m above the barrier.

4

5 *Steady state conditions.*

6

7 The transport by advection alone reaches a steady state when the concentration throughout the

8 barrier Cs_i = the concentration above it Cs_0.

9

10 Thus $F = V \times Cs_0$ $\qquad\qquad \ldots[6]$

11

12 The transport by diffusion alone reaches a steady state when there is a linear concentration gradient

13 through the barrier.

14

15 The flux is given by:

16

17 $$F = \frac{Cl_0}{\left(\dfrac{x_1}{D_1 \times \varepsilon_1} \right) + \left(\dfrac{x_2}{D_2 \times \varepsilon_2} \right) + \left(\dfrac{x_3}{D_3 \times \varepsilon_3} \right)} \qquad \ldots[7]$$

18

19 These values are calculated at the start of the programme.

20

21 *Time step*

22

23 The time step dt for the programme is set to an estimated value and the time to breakthrough is

24 calculated. The time step is then halved and the process is repeated. A change of less than 5% in

25 the breakthrough time is taken to indicate stability.

26

27 The relationship between the time step and the cell size is initially determined by the advection

28 calculation. This can mean that if the diffusion flux is high the concentration in the cell can change

29 substantially during a single time step (it is assumed to remain approximately constant). This is

6

1 checked and if the resulting change in concentration in the cell exceeds 25% of the concentration

2 the time step is reduced.

3

4 *Advection calculation*

5

6 The advection from cell i to cell i+1 during a single time step dt is calculated as:

7

8 $F \times dt = Ct_i \times \varepsilon_i \times Cl_i = dt \times V \times Cl_i$ ...[8]

9

10 where the cell thickness $= Ct_i$

11

12 *Diffusion calculation.*

13

14 The diffusion from cell i to cell i+1 during a single time step dt is calculated as:

15

16 $$F = \frac{\varepsilon_i \times \left(\dfrac{D_i + D_{i+1}}{2}\right) \times \left(Cl_i - Cl_{i+1}\right)}{Ct_i}$$ ...[9]

17

18 For the upper and lower cells (numbers 1 and n) the diffusion is doubled because the diffusion path

19 to the centre of the cell only runs through half the distance of solid.

20

21 *Optimisation.*

22

23 The programme is used for a single run when calculating the performance of a landfill cell but when

24 calculating the properties of a sample (diffusion coefficient and capacity factor) from experimental

25 results it can carry out repeated runs and optimise. For each run the root mean square error between

26 the model results and the experiment is calculated and the sample properties are then adjusted to get

27 the lowest error.

28

29 *Treatment of tolerances.*

30

31 The input data for the modelling of the full-scale barriers (e.g. layer thickness) is assumed to be

32 normally distributed. For the purpose of modelling it is divided into three outcomes, an expected

outcome and one high and one low. Studying the normal probability function shows that to give each outcome equal probability the expected outcome must include all results within 0.43 standard deviations of the population mean. The mean of the high and low outcomes have been calculated to be 1.1 standard deviations above and below the sample mean. The standard deviation has been estimated as a coefficient of variation V = standard deviation/mean. Thus 3 outcomes were modelled and these are shown in Table 1.

For the diffusion coefficient and the permeability the treatment is slightly more complex in that the distribution of results form a highly skewed distribution when measured on a linear scale. On a logarithmic scale they are, however, more normally distributed and the three different outcomes have therefore been obtained by dividing up the distribution of the log of the parameter. The three outcomes for this case are shown in Table 2 where V is the coefficient of variation of the sample on a logarithmic scale.

Typical values are as follows for the parameters are shown in Table 3. From this it may be seen that although V for permeability appears low at 2% it represents a range of +60% and −36% on a linear scale. The 5% for diffusion gives an increase of 460% on a linear scale.

Because the populations are skewed on a linear scale the mean outcome from this analysis is not the outcome with the highest probability (as would by expected from a normal distribution).

Each of these outcomes has been modelled for each input parameter for which there is significant uncertainty. Thus, for example, where four different input parameters have significant uncertainty 81 simulations have been carried out and the 10th and 90th percentiles of the resulting population have been used to calculate the degree of uncertainty of the model predictions.

The coefficients of variation for the input data obtained in the laboratory work have been obtained by studying several series of replicate samples and also analysing the optimisation of the data from the through diffusion tests.

Some variables, such as layer thickness in multi-layer barriers, are in sets in which varying each one will have a similar effect. Reducing the thickness of one layer by 20mm will have a similar effect to reducing another layer. In there situations only the variation of one of the variables has been modelled.

1

Model Code Validation

3

The model code has been validated as follows:

5

The steady state values can be checked by hand calculation and for a number of different configurations the programme has been run for long enough to reach an effective steady state and the output checked for agreement.

9

For a single layer the model has been checked for agreement with the PHREEQE transport code (4) for a single element.

12

MIX DESIGNS

14

The mix designs are shown in table 4. The designs were chosen to make use of available industrial wastes and give an adequate strength (5 MPa) and permeability (10^{-9} m/s) (5,6).

17

LABORATORY TESTING

19

Tests were carried out on samples taken from the mixes at the time or the pours for the site trials.

21

Diffusion Tests

The diffusion cells were used to examine mass transport in reactive systems. An aggressive solution, simulating an acetogenic leachate typical of the early stages of landfill evolution (see table 5) was allowed to react with the sample, whilst concentration changes due both to diffusion and reactive transport were monitored in the cells.

27

This application of the diffusion test is intended to measure both the diffusion coefficient and capacity factor of those species partitioned between the solution and porous sample. The basis of the test is a divided cell with the sample in the centre. Artificial leachate is placed on one side and deionised water on the other; chemical analysis is used to track changes with time on each side.

32

1	The apparatus is a modified ASTM (C1202) test. The C1202 test has an applied electric field and

2	in this work the same cells were used without the field but with extra reservoirs on the top. Using

3	an electric field would have accelerated the tests but made interpretation very uncertain.

4

5	Two symmetric poly methyl methacrylate ('Perspex') chambers with fluid reservoirs of 85 mm

6	diameter and about 47 mm depth were made with extra liquid storage reservoirs of 50 ml on top of

7	the chambers. Figure 1 shows the arrangement of cells and the specimen between them. The

8	specimens are a 100 mm diameter disc with about 10 mm thickness.

9

10	The specimen-cell is sealed by using rubber gaskets on each side of the specimen, tightening the

11	bolts, and applying silicone rubber round the specimen and inner face of cells. The apparatus was

12	kept in a temperature controlled room at 20°C. Periodically, 10 ml of liquid was taken out from the

13	reservoirs and the chemical composition was analysed using Inductive Coupled Plasma (ICP)

14	analysis.

15

16	Synthetic leachate was used on one side of the sample and de-ionised water on the other.

17

18	From the diffusion tests on the mixes used for the site cell capacity factor (α) and D (diffusion

19	coefficient) values were calculated using the optimisation routine in the computer model

20

21	The modelled input – output and experimentally measured (real) input- output concentrations of the

22	diffusion cell are plotted for two typical examples in figures 2 and 3. The results show that, for the

23	limited data used, the model optimisation gave a very good agreement between the modelled values

24	and the experimental values. This was achieved by the progressive changing of the capacity factor

25	and diffusion coefficient by the optimisation routine. In figure 2 increasing either parameter

26	increases the transport into the sample and will thus increase the rate of decline of the input

27	concentration. The output concentration will, however, change more if the diffusion is increased

28	but the adsorption is decreased. In figure 3 a high initial concentration in the sample (measured by

29	pore fluid expression and input into the model) gives a rising concentration on both sides of the

30	sample.

31

32	The derived results for diffusion and adsorption are in Table 6.

33

Permeability Tests

The permeabilities of the specimens were determined using a continuous high-pressure flow experiment in which solution is eluted through the materials at pressures up to 10 MPa depending on the compressive strength of the particular specimen. The apparatus is adapted to measure both the flow and pressure drop across the sample. Measurements were made after one sample volume of liquid had passed through the concrete or mortar specimens. Assuming an average permeability of 10^{-9} and a maximum leachate head of 1 m above the liner, this corresponds to 16 years of exposure in service. The results are in Table 7.

Pore Fluid Concentrations

Samples of pore fluid were expressed under pressure from samples of the different mixes using a cell similar to an OPI-CAD cell (6) and the concentrations obtained from them using ICP analysis.

SITE TRIALS

Two cells were constructed on a licensed landfill operation site at Risley, Cheshire UK in winter 2000 with different cementitious composite mineral waste materials (7). This landfill site receives both domestic and industrial waste. These cells were numbered 2 and 3 are still being monitored (cell 1 has been dismantled due to site requirements and is not reported here).

The purpose of the cells is as follows.

- To provide validation data for the modelling of the performance of the barriers in service.
- To demonstrate a construction method.
- To demonstrate that the novel mixes can be made in industrial quantities (150 tonnes of concrete were used in the three test cells).
- To provided samples for on-site workability testing and long-term physical testing in the lab.
- To provide samples for mineralogical analysis when the cells are dismantled.

 Layout and construction methods of the cells:

1   A typical test cell is shown schematically in Figure 4. The barrier is made up of two layers of

2   concrete with a layer of clay between them. These inverted pyramid shape cells measure 8 metres

3   wide and contain waste to a maximum depth of 1.1 metre. The slopes of the cells are 30° and the

4   cells contain 5.4 m^3 of waste. Table 8 gives the dimensions and volume of each layer in the test

5   cells. The excavation was carried out with an excavator which was also used to place the concrete

6   and mortar mixes designed for the different cells. The concrete layers were placed and levelled by

7   the excavator. The compaction of concrete layers was carried out by two poker vibrators and the

8   compaction of clay layer was carried out using the outside surface of the excavator's bucket.

9

10   *Observations from the construction*

11

12   During the construction of cell numbers 2 and 3 the mix proportions actually used were different to

13   what was designed in Laboratory due to some practical problems encountered in the batching plant

14   and placement of some of materials (inaccurate weightings of different materials and partial

15   hydration of CKD while stored at the plant). The mixes actually made were tested and showed

16   higher permeabilities than the mixes designed initially in the laboratory.

17

18   **Emplacement of waste and leachate**

19

20   Due to size and shape constraints of the cells shredded waste was used. It was placed and

21   compacted up to the top level of the test cells. A leachate which provided the most aggressive

22   solution representing the leachates found in the landfill was obtained from the leachate treatment

23   plant for the site and the cells were filled 100 mm below the top giving a 1 m head at the deepest

24   point. The cells were covered with a tarpaulin rain cover to prevent rainwater ingress and contain

25   odour.

26

27   **Instrumentation and sampling**

28

29   Two types of sampling lines were used between the layers of the cell liners using 3 mm plastic

30   tubes in both. In one type the end of the 3 mm plastic tubes were glued inside porous stone discs of

31   60 mm diameter. In the other type the layer was drilled and the 3 mm plastic tubes ends were sealed

32   in place in the set concrete with sponge around the end of the line. The sampling lines were placed

1 as an array in the various liner materials and levels. Liquid samples were obtained by applying a

2 vacuum to the lines.

3

4 **Operation of Vacuum Lines**

5

6 On the end of the extract lines there is a sponge or a stone to form a void. If there is gas in adjacent

7 pores or cracks etc. samples may be extracted easily with a vacuum. If there is no gas or other

8 pathway the flow up the line must be from advection from a spherical region around the void.

9 Solving the equation for permeable flow into a spherical void the velocity of flow up the pipe is

10 given by:

11

12 $$V = \frac{4khr_1}{r_0^2} \quad m/s \qquad\qquad [10]$$

13

14 where:

15 k is the permeability (10^{-9} m/s)

16 h is the head of water corresponding to the atmospheric pressure (m)

17 r_1 is the radius of the void (10mm)

18 r_0 is the bore radius of the pipe (1.5mm)

19

20 The outer radius of the integral is insignificant provided it is much greater than r_1. Using the values

21 in brackets gives a calculated flow of 640mm per hour. Flow rates of approximately this value were

22 observed.

23

24 **Modelling transport in the tests cells**

25

26 Cell 3 needed to be refilled after 12 months. The reason for this was inadequate compaction of the

27 clay layer leading to an increased permeability. The effective indicated premeability was calculated

28 as follows:

29 Total Volume of the leachate leaked $\cong 4.54$ m^3

30 Surface area of pyramid in bottom of clay layer = 25.3 m^2

31 Thus indicated permeability k = 5.2 $\times 10^{-9}$ m/s

1   This corresponds to nearly the same permeability as a Bentonite Enhanced Sand liner and indicates

2   satisfactory performance even when very poor construction practice was evident but id did affect the

3   modelling considerably. The permeability calculated from these site observations was therefore

4   used for the clay layer.

5

6   **Comparison between model and observations**

7

8   The capacity factor, alpha (α) and diffusion coefficient (D) values obtained from the diffusion tests

9   on the top and bottom mixes used in the site trial cell number 2 and 3 together with the initial

10 concentrations of different elements in site leachate and the mixes used in the cell (from pore

11 pressed solutions) were used (see table 9) to verify the modelled concentration against measured

12 collected sample concentration values. These are shown in figures 5 to 12 for Ca, Na and K for cells

13 2 and 3 respectively.   On these graphs error bars are shown between the 10th and 90th percentiles

14 from the probability calculations at ages of two and four years (in figures 8,9 and 10 these have

15 been offset slightly for clarity). The coefficients of variation used for these are shown in Table 10.

16 The observed concentrations which are shown on the graph are based on the average from up to

17 four different sample taken in different parts of the cells. For some of these a considerable spread

18 of results was recorded.

19

20 In figure 5 the fall in Ca concentration at the bottom of the clay in cell 2 is somewhat slower than

21 predicted but the error bars (which included a range of permeabilities in their calculation) allow for

22 this and cover the range of observed data. The very slow rise at the top of the clay is well predicted.

23

24 In figure 6 the rapid rise of the sodium concentration at the top of the clay follows the predictions

25 within the range of the error bars. Some instability in the model may be seen at 3-4 years. This

26 could be solved at the expense of increasing the run time but is not considered relevant within the

27 accuracy of the whole model. The results at the bottom of the clay are not explained at all. There is

28 an unexplained source of sodium.

29

30 For the potassium in figure 7 the decline at the top of the clay lies just within the error bars but there

31 is again an unexplained trend at the bottom.

32

In cell 3 figure 8 shows the calcium rising at the bottom of the clay. The model shows it falling and the error bars show that no changes in the input data lead to a predicted increase. The agreement at the top of the clay is, however, good with a rise occurring as predicted but somewhat earlier.

In figure 9 the observed data from both sets lie within the range given. The rise and fall predicted for the bottom of the clay appears to be occurring in the site data at a lower level than expected but within the error bars. The observed increase at the top of the clay after 3 years is not predicted.

In figure 10 the expected increase in potassium at the bottom of the clay has not occurred however the error bars give a very wide range due to uncertainty about the time when this will occur. The data for the top of the clay lies within the error bars.

It has been observed (8) that transport processes in landfills are associated with a high degree of uncertainty. The processes modelled in this paper used real landfill leachate which was undergoing biological reactions throughout the experiment and took place in a site environment with all of the associated uncertainty. The combination of these factors with the uncertainty associated with the stated assumptions in the model has given rise to some unexpected events. Nevertheless this is a useful exercise to indicate likely trends in a real environment. Long term results which will involve transport processes far closer to the steady state are actually likely to be more accurate. Further, and more complex, calculations are being carried out using the PHREEQE code for coupled chemical transport but the number of unknowns is limiting these to single layers of the barrier.

Conclusions

1. Transport through concrete barriers may be modelled using simple computer programmes which apply the transport equations directly.

2. Site trials have shown that the model provides a useful estimate but revealed some unexplained data.

Acknowledgements

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28

Outcome	Mean value	Probability
high	sample mean * (1 + 1.1 V)	0.33
expected	sample mean	0.33
low	sample mean * (1 - 1.1 V)	0.33

Table 1 Probabilities for parameters with a linear distribution.

Outcome	Mean value	Probability
high	sample mean ^ (1 - 1.1 V)	0.33
expected	sample mean	0.33
low	sample mean ^ (1 + 1.1 V)	0.33

Table 2 Probabilities for parameters with a logarithmic distribution

Parameter	Typical Value	Scale	Coefficient of variation %	Low value	High value
Capacity factor	5	Linear	50	2.25	7.75
Permeability	10^{-9}	Logarithmic	2	6.4×10^{-10}	1.6×10^{-9}
Diffusion Coefficient	10^{-12}	Logarithmic	5	2.2×10^{-13}	4.6×10^{-12}
Layer thickness	300	Linear	15	250.5	349.5

Table 3   Typical values and ranges for the measured parameters.

1

	Proportions Used	
	kg/m^3	% By mass
Composition of top layer mortar for cell No.2:		
Ferrosilicate slag sand (< 5 mm)	1575	65.9
Cement Kiln Dust – 60%	490	20.5
Lagoon Ash – 40%	325	13.6
Water	200	
Composition of top layer concrete for cell No.3:		
Ferrosilicate slag (< 150 mm to dust)	0	
Limestone (<20 mm)	715	29.8
Ferrosilicate slag sand (< 5 mm)	1105	46
Cement Kiln Dust – 60%	340	14.2
Lagoon Ash – 40%	240	10
Water	220	
Composition of lower layer concrete for cell No.2:		
Chrome Alumina Slag (< 40 mm)	1175	49.6
Chrome Alumina Slag (< 5 mm)	720	30.4
Green sand	100	4.2
Cement Kiln Dust – 60%	165	7
T1Sodium sulphate Solution (lt)	165	
Composition of lower layer concrete for cell No.3:		
Chrome Alumina Slag (< 40 mm)	1175	50.3
Chrome Alumina Slag (< 5 mm)	720	30.8
Green sand	110	4.7
Portland Cement – 5.2% CEM1 42.5N to BSEN 197-1	25	1.1
Cement Kiln Dust – 69.8%	185	7.9
Lagoon Ash – 25%	120	5.2
Water	240	

2

3   ***Table.4:*** *Composition of mixes used in the three trial cells.*

4

1

2.043 g	Concentrated Sulphuric acid
4.48 g	Acetic acid
1.897 g	Potassium chloride
7.755 g	Calcium acetate
1.186 g	Ammonium chloride
0.91 g	Sodium chloride
2.588 g	Sodium hydroxide

2

3 *Table 5 Composition of synthetic leachate, per litre of solution (pH=5.1)*

4

Chemical Element	Top layer mix Cell 2 & 3 (Porosity = 12%)		Bottom layer mix Cell 2 (Porosity = 9%)		Bottom layer mix Cell 3 (Porosity = 9%)	
	α	D	α	D	α	D
Ca	7.74	3.7×10^{-10}	0.5	1.77×10^{-10}	0.09	1.35×10^{-10}
Na	0.43	1.19×10^{-10}	0.09	10^{-14}	1	4.58×10^{-13}
K	0.86	1.07×10^{-10}	1.02	1.71×10^{-12}	1	6.73×10^{-12}
S	1	2.07×10^{-12}	1.37	10^{-14}	27.67	2.93×10^{-14}

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6 **Table 6:** Capacity factor (**α)** and D (diffusion coefficient) values for the four major elements in the

7 trial cells.

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	7 days strength (MPa)	28 days strength (MPa)	Intrinsic permeability to water @ 28 days (m/s)	Intrinsic permeability to leachate @ 28 days (m/s)
Cell 2 top	1.1	1.7	4.5×10^{-9}	5×10^{-9}
Cell 2 base	4.4	6.9	2.3×10^{-9}	4.5×10^{-9}
Cell 3 top	0.9	1.3	1.2×10^{-8}	7.5×10^{-9}
Cell 3 base	2.8	6.0	1.2×10^{-8}	6.2×10^{-9}

2

3   *Table 7: Characteristics of the mixes used in the site trial cells.*

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	Thickness (m)	Depth to lowest point (m)	Width (m)	Volume (m^3)
Waste	-	1.1	3.84	5.4
Upper Concrete	0.2	1.33	4.65	4.16
Clay	0.5	1.9	6.66	18.61
Lower Concrete	0.3	2.25	7.87	18.28

5

6   *Table 8: Dimensions and volume of each layer of test cells.*

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Elements	Site leachate	Cell 2			Cell3		
		Top layer	Clay layer	Bottom layer	Top layer	Clay layer	Bottom layer
Ca	344	4	350	1214	4	350	14
Na	2300	450	450	10802	450	450	2157
K	4730	15193	300	1761	15193	300	761
S	770	2000	500	549	9294	500	50

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9   *Table 9 Initial liquid concentrations used in models for site trials (mg/l).*

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Parameter	V%	Distribution Used
Capacity factor	50	Linear
Diffusion coefficient	4	Logarithmic
Permeability	3.165	Logarithmic
Layer Thickness	15	Linear

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3   Table 10. Coefficients of variation for parameters used in the modelling.
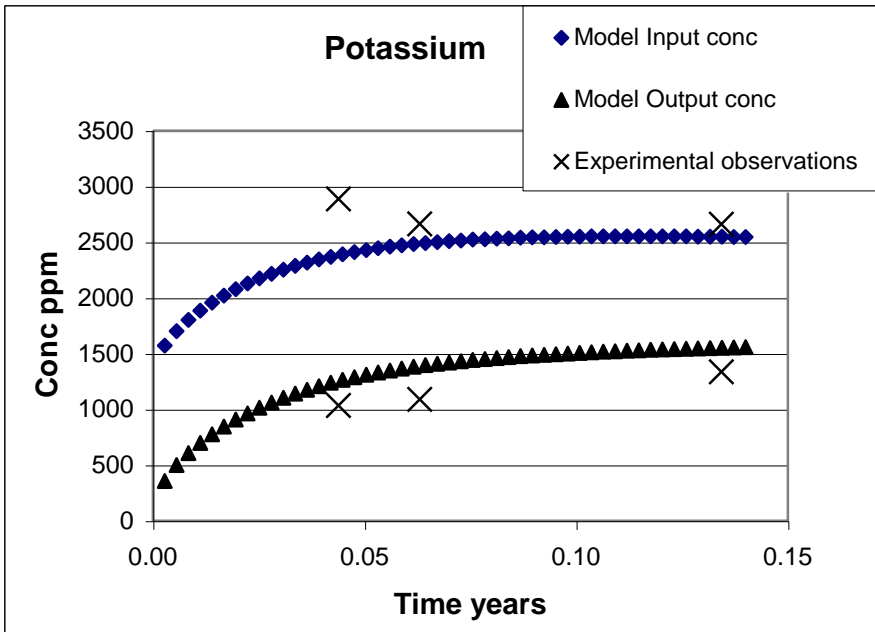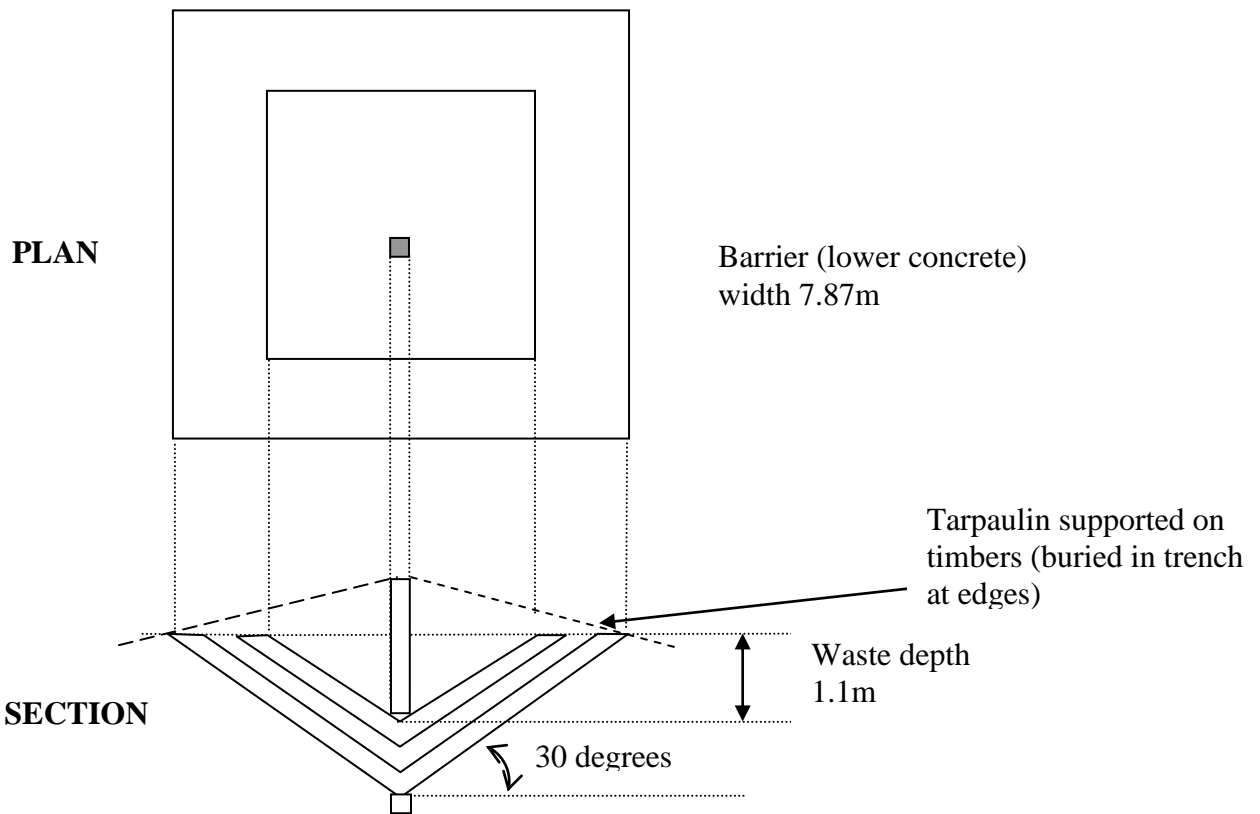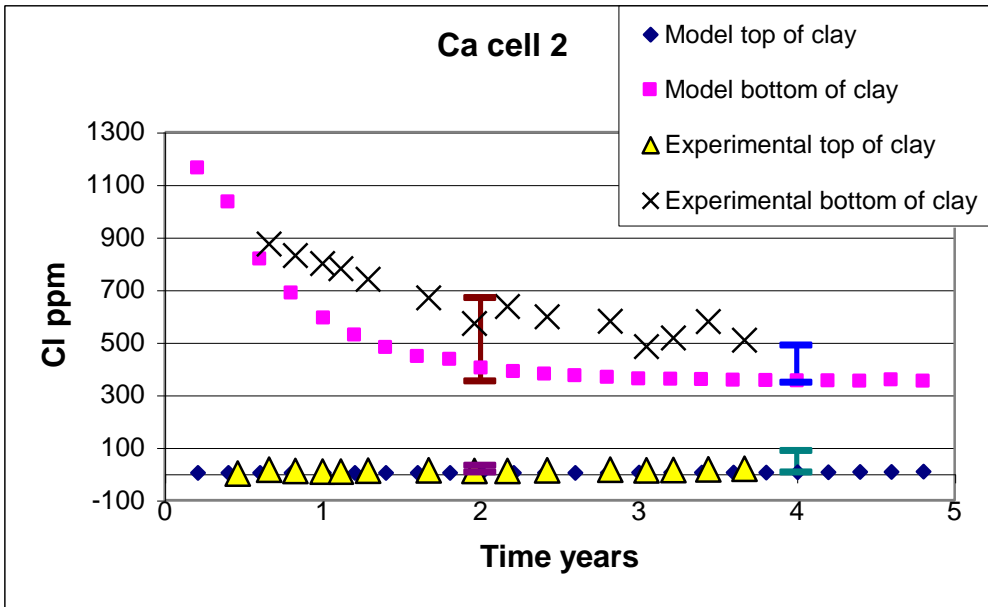
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3   *Fig.1 Diffusion cells.*
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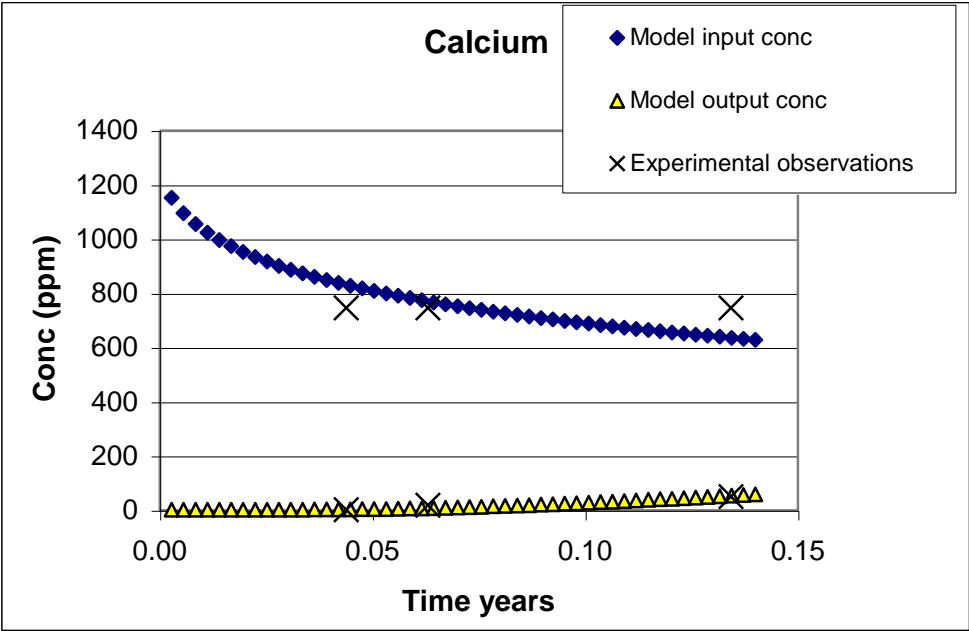
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7   Figure 2 Concentrations from laboratory diffusion testing for calcium
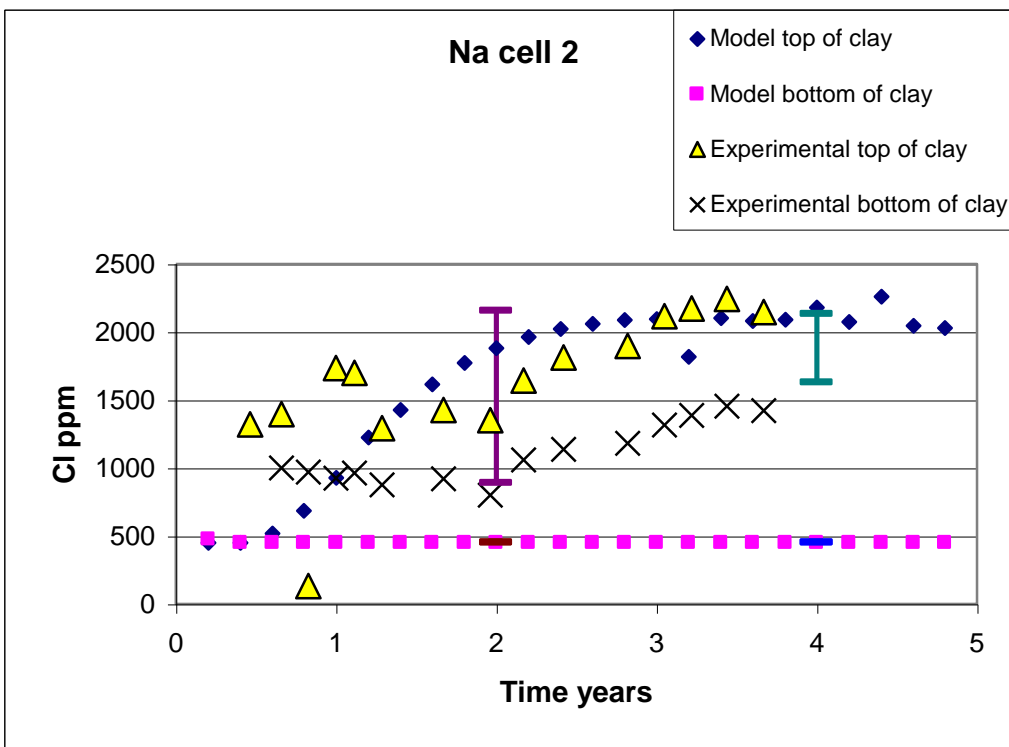
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2   Figure 3 Concentrations from laboratory diffusion testing for potassium

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5   *Figure4: Typical trail test cell layout.*

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2   Figure 5 Concentrations of calcium in site trial cell 2

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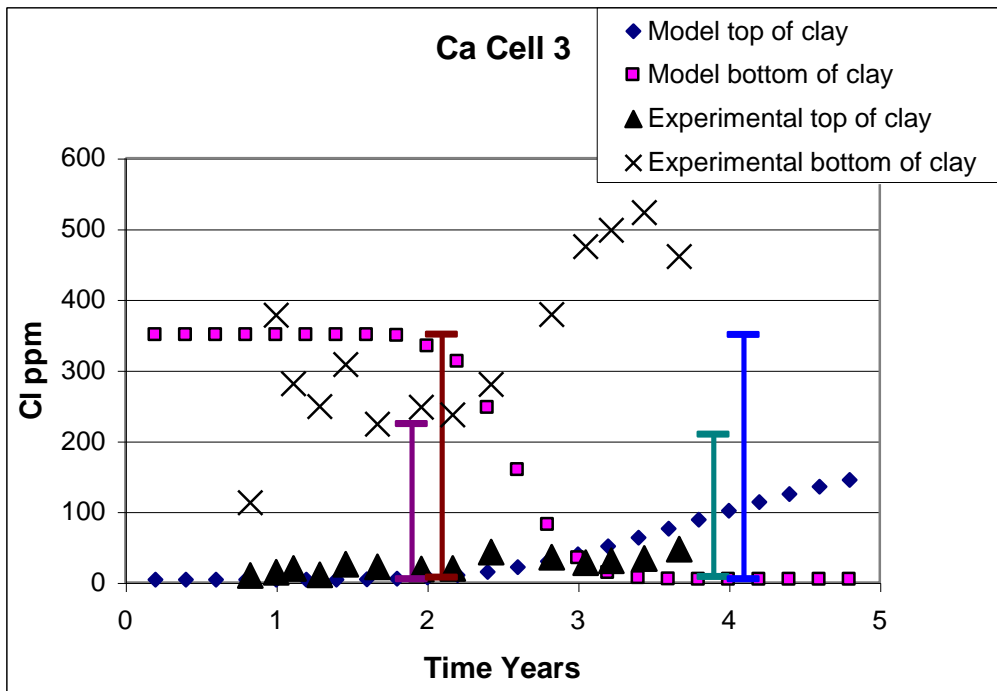4   Figure 6 Concentrations of sodium in site trial cell 2
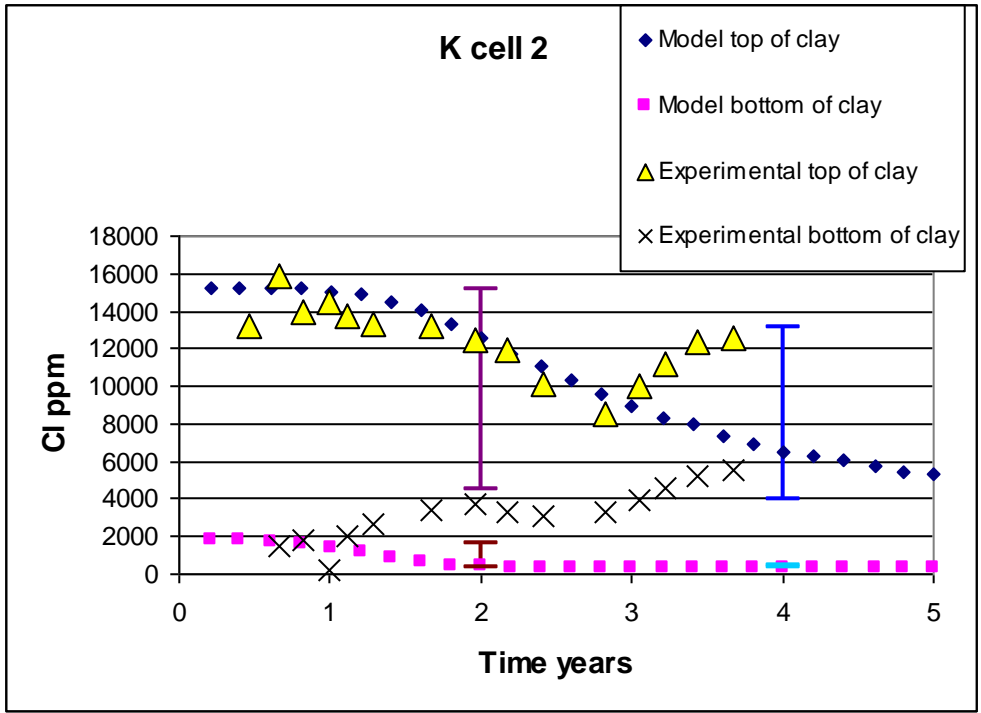
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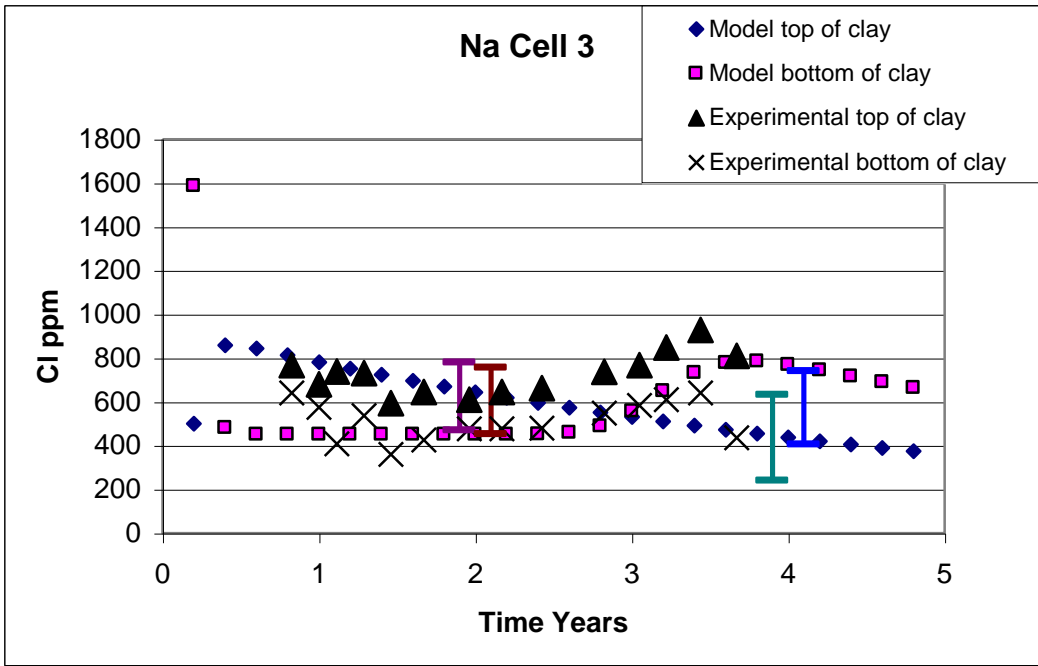2   Figure 7 Concentrations of potassium in site trial cell 2

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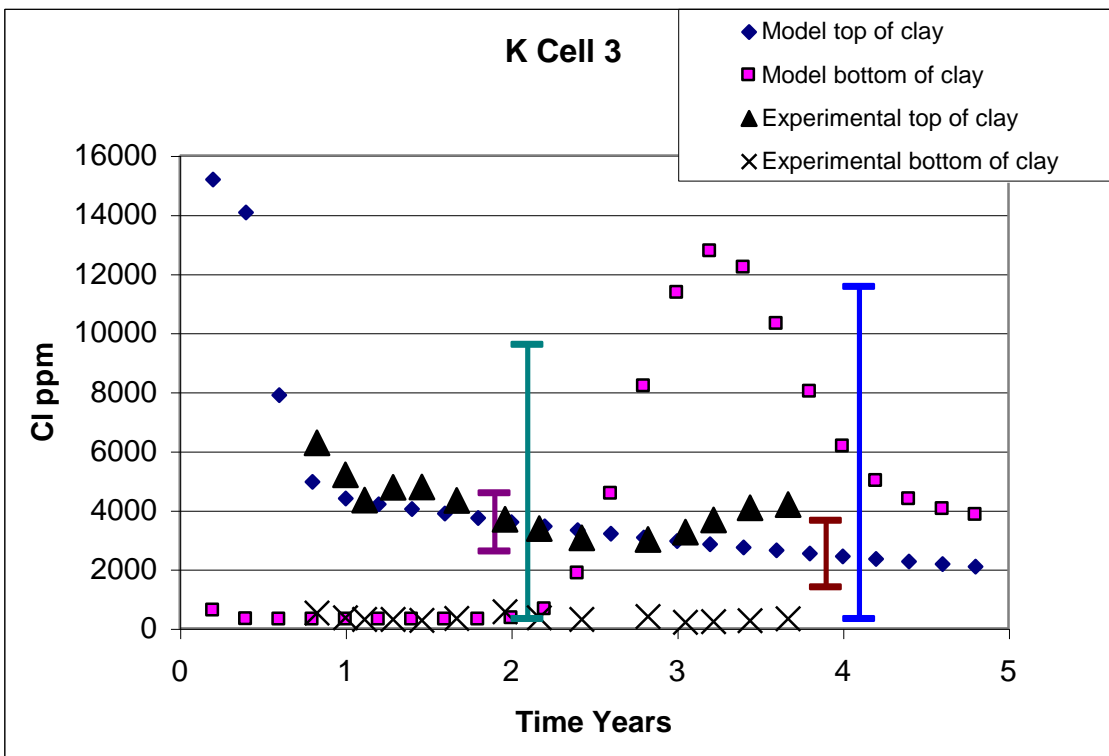5   Figure 8 Concentrations of calcium in site trial cell 3

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2   Figure 9 Concentrations of sodium in site trial cell 3

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6   Fig 10 Concentrations of potassium in site trial cell 3