

For citation information please see <http://www.claisse.info/Publish.htm>

Transport Properties of Concrete: Measurement and applications

Professor Peter A Claisse
Coventry University, Coventry UK



Transport Properties of Concrete: Measurement and applications

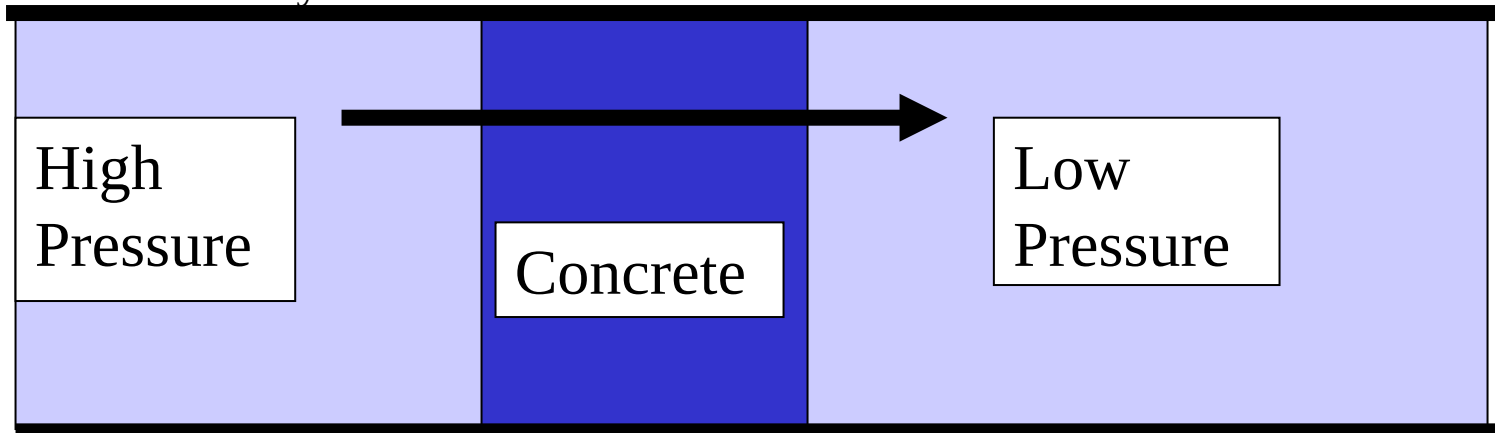
- The transport processes
 - Pressure driven flow
 - Diffusion,
 - Electromigration
 - Thermal migration
- Processes which promote or inhibit transport
- Surface permeability tests
- Electrical tests
- Application of the results

Pressure driven flow (permeation or advection)

- Water (which may contain salt) flows in the direction of the applied pressure.
- The flux F depends on the pressure gradient dP/dx

- K = permeability
- A = Area
- E = viscosity

$$F = \frac{KA}{e} \frac{dP}{dx} \quad m^3/s$$



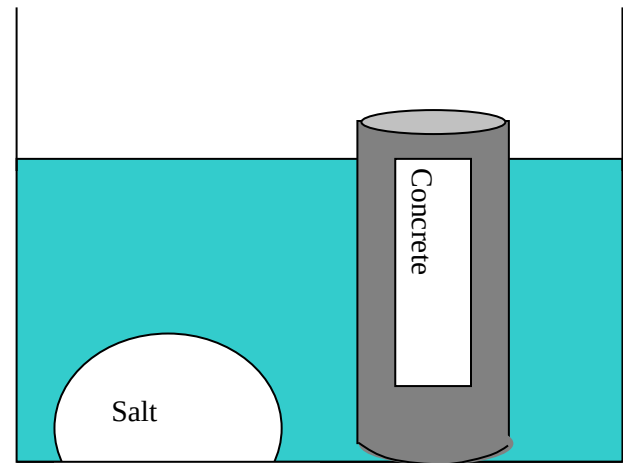
Diffusion

When the salt dissolves into the water it will assume an equal concentration at all points throughout the liquid and will enter the concrete

The flux depends on the concentration gradient dC/dx

$$F = D \frac{dC}{dx} \quad \text{kg/m}^2/\text{s}$$

D = diffusion coefficient

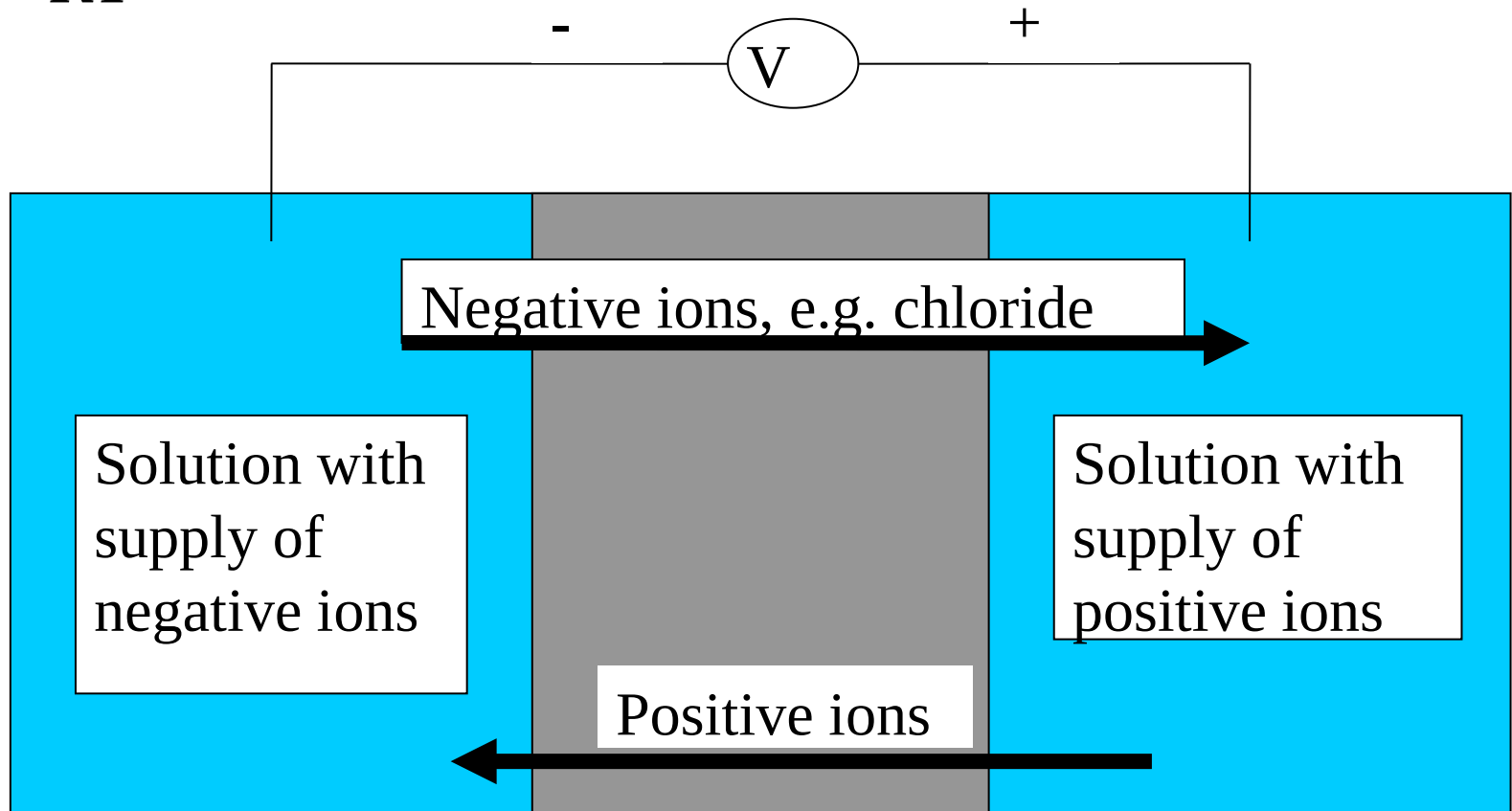


Electromigration

The flux depends on the electrostatic field E
i.e. the voltage gradient (Volts/m)

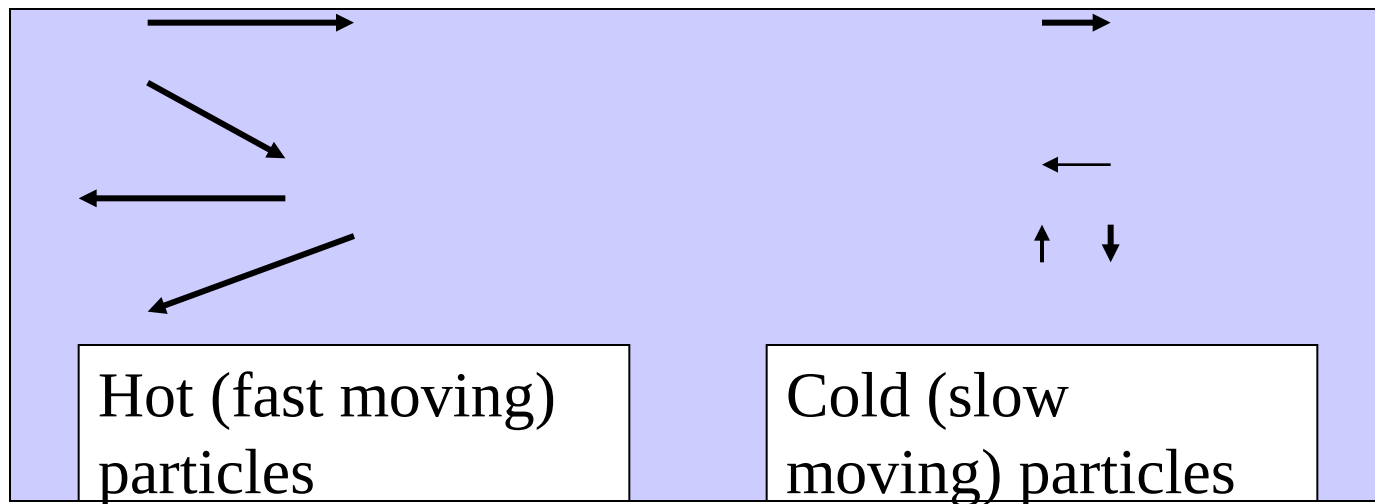
$$F = \frac{DzECF}{RT}$$

Z = valence, R = gas constant, T = temperature



Thermal Gradient

A concrete structure which has been contaminated with de-icing salt heats up in sunlight



Transport Properties of Concrete: Measurement and applications

- The transport processes
- Processes which promote or inhibit transport
 - Adsorption (inhibits)
 - Capillary suction (promotes)
 - Osmosis (promotes)
- Surface permeability tests
- Electrical tests
- Application of the results

Adsorption

Adsorbed ions are fixed into the matrix in various ways and are unable to move and therefore unable to cause any deterioration.

The ratio of total concentration (including adsorbed ions) to concentration in solution is the “capacity factor”.

Definitions

C_l : free ions per unit volume of liquid
(pore solution)

C_s : total ions per unit volume of the solid
(concrete)

α : capacity factor

ε : porosity

$$\alpha = \frac{C_s}{C_l}$$

$$F = D_{app} \frac{dC_s}{dx}$$

The flux is calculated per unit area of the porous material (concrete) and the average concentration in the concrete

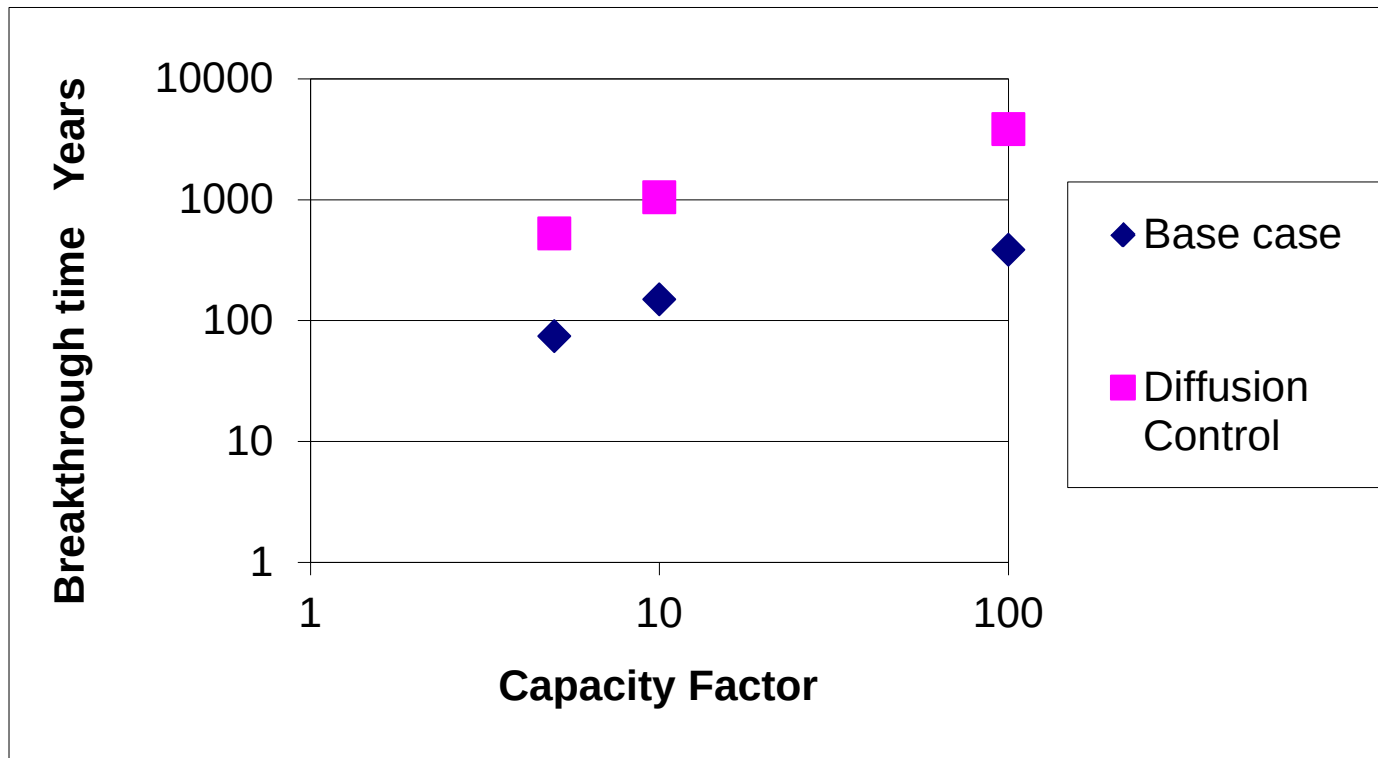
$$F = \varepsilon \cdot D_i \frac{dC_l}{dx}$$

The flux is calculated per unit cross-sectional area of the pores and the concentration in the pore solution

$$\frac{\alpha}{\varepsilon} = \frac{D_i}{D_{app}}$$

The effect of adsorption

(Calculations from a computer model).



Capillary Suction

Water rises up a small diameter glass capillary tube to a height h

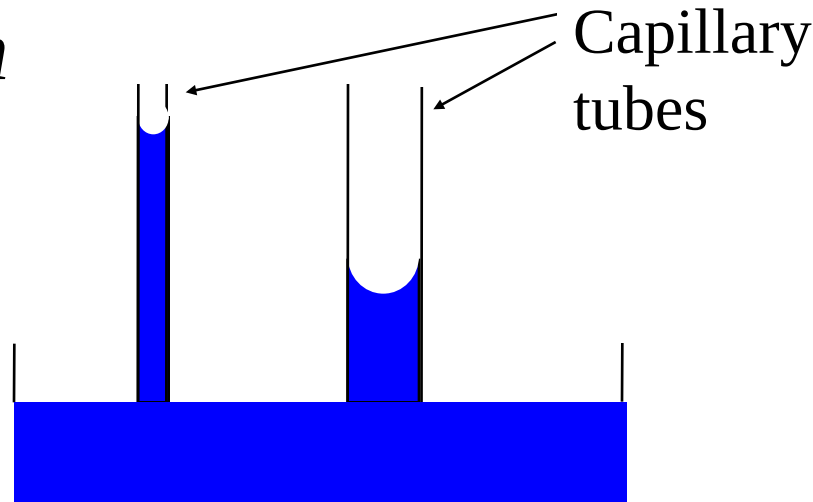
$$h = \frac{2s}{r\rho g} \quad m$$

s = surface tension

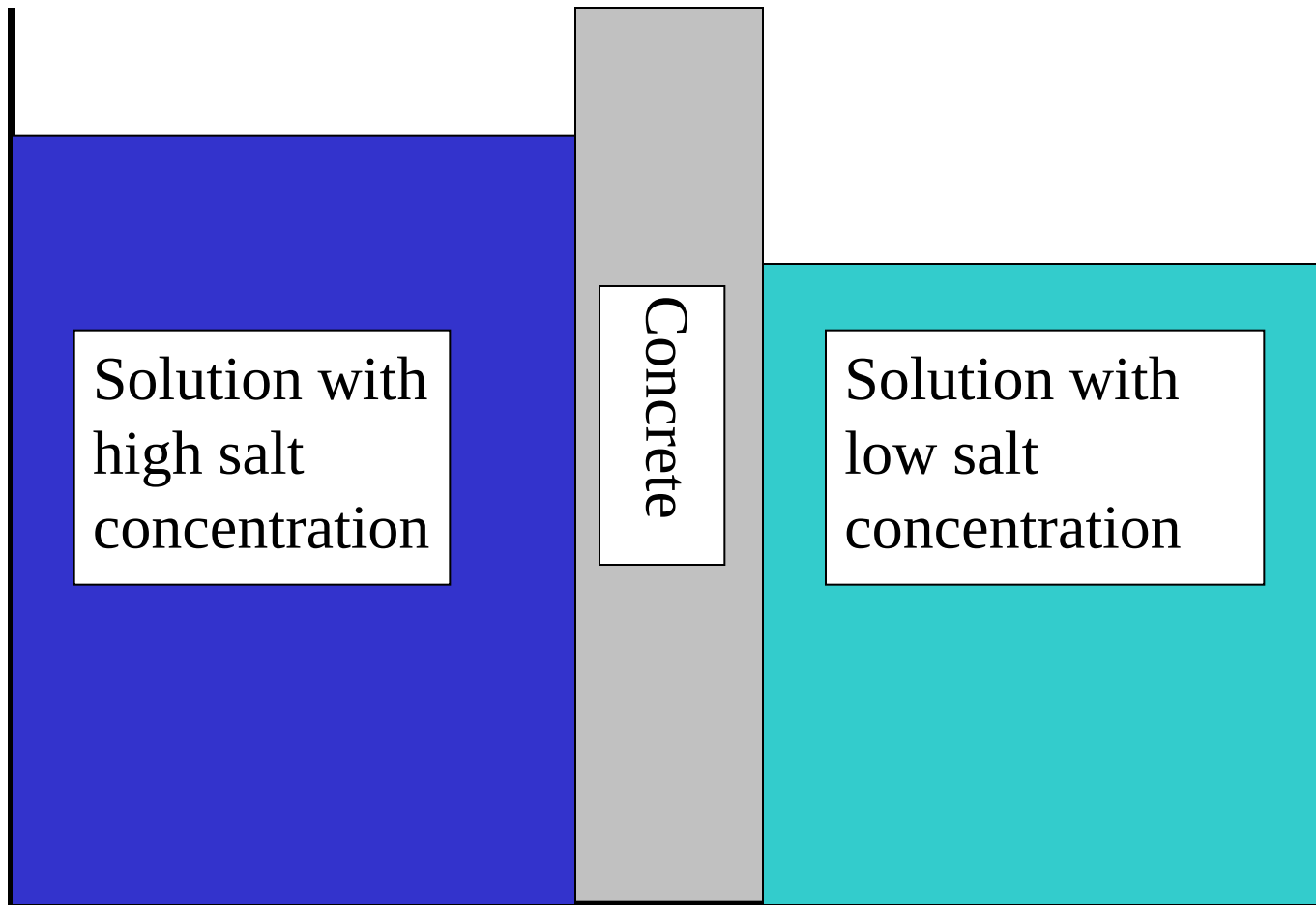
r = pore radius

ρ = density

g = gravitational
constant



Osmosis

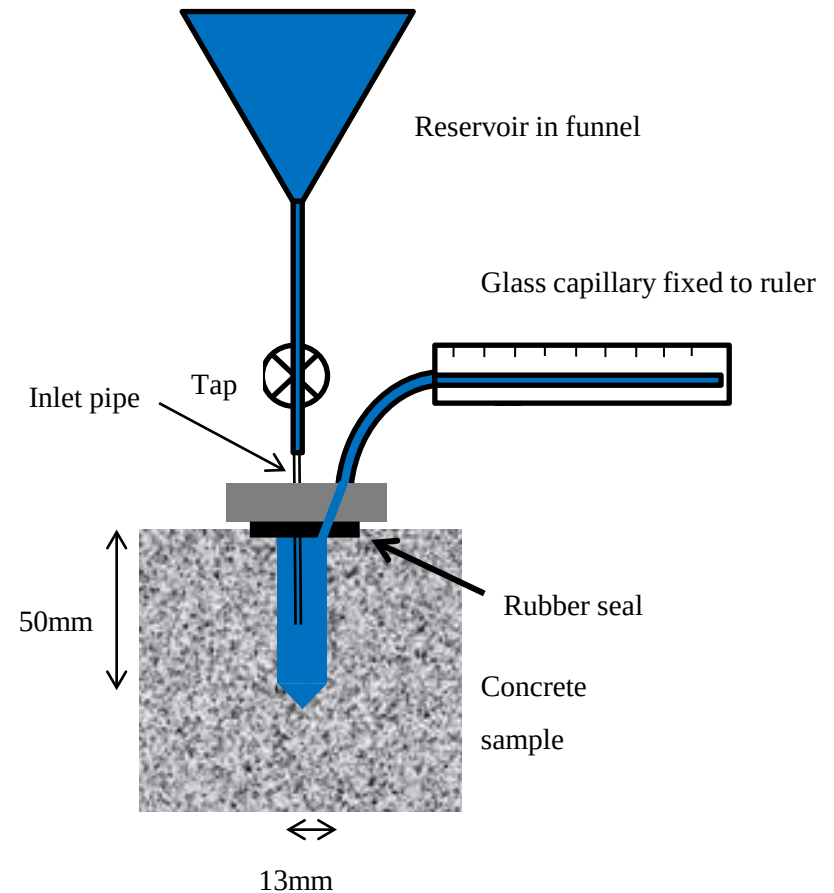
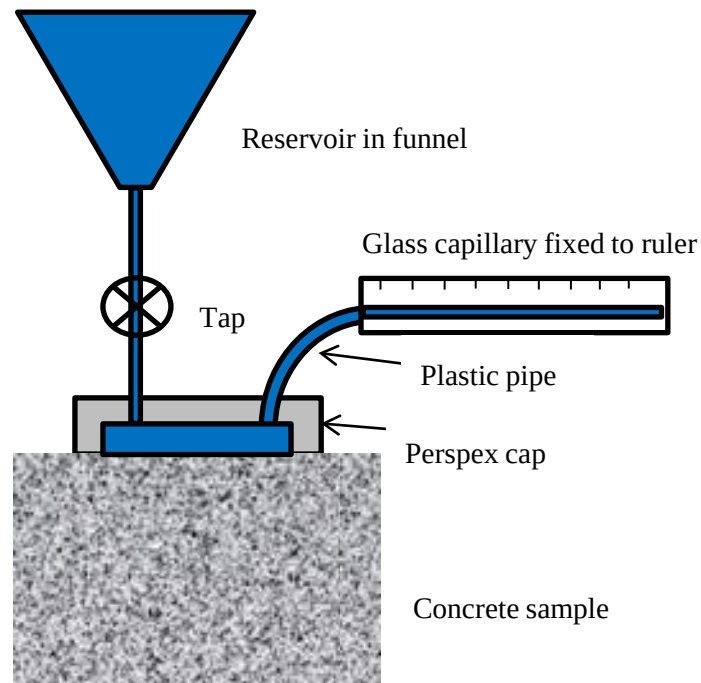


Transport Properties of Concrete: Measurement and applications

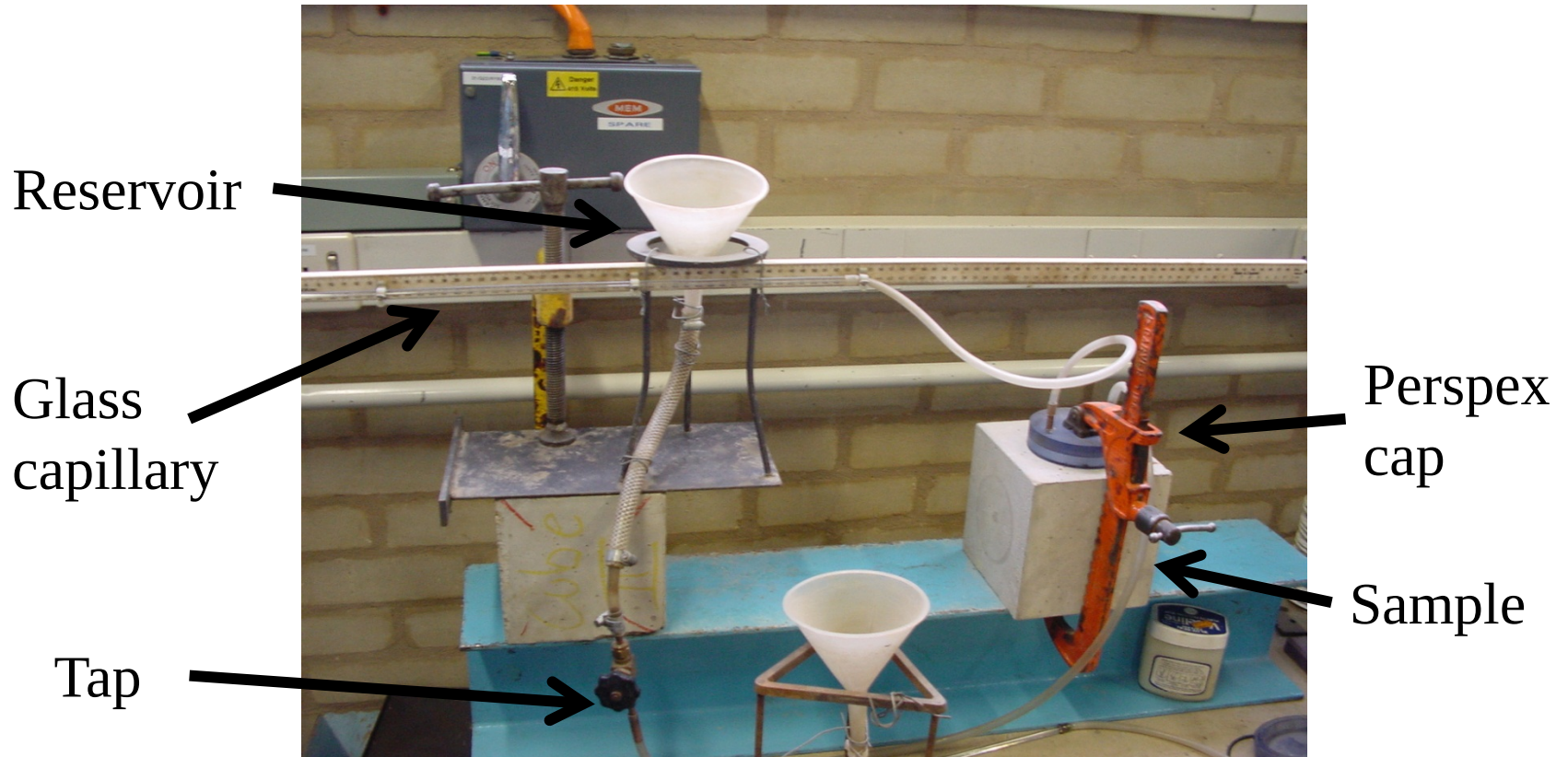
- The transport processes
- Processes which promote or inhibit transport
- Surface permeability tests
 - Tests using water
 - Tests using a vacuum
- Electrical tests
- Application of the results

Surface tests using water

ISAT and Cover Concrete test

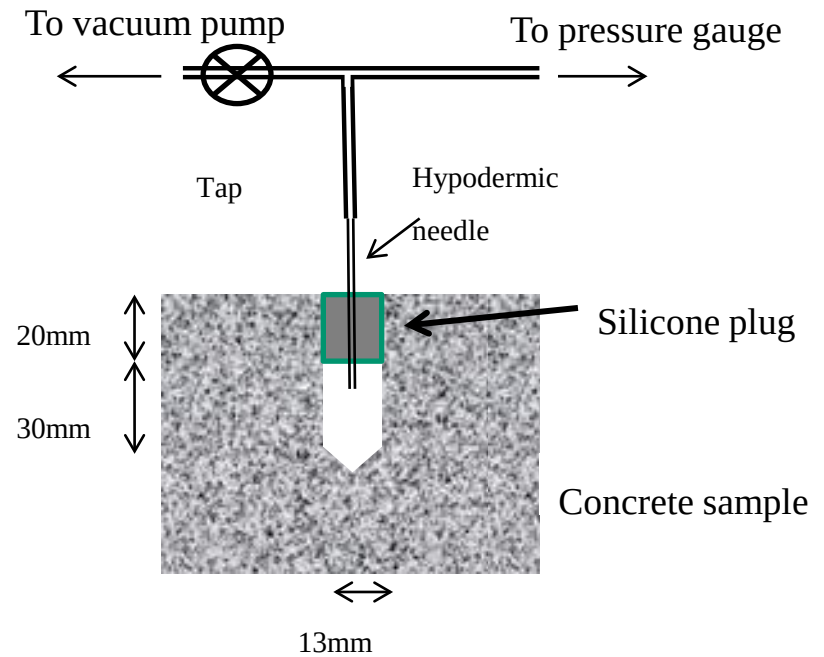
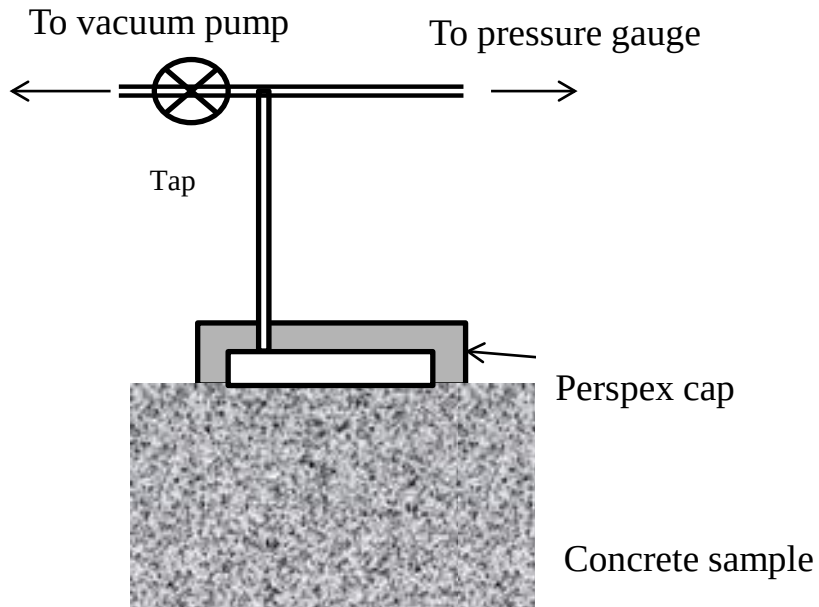


ISAT apparatus

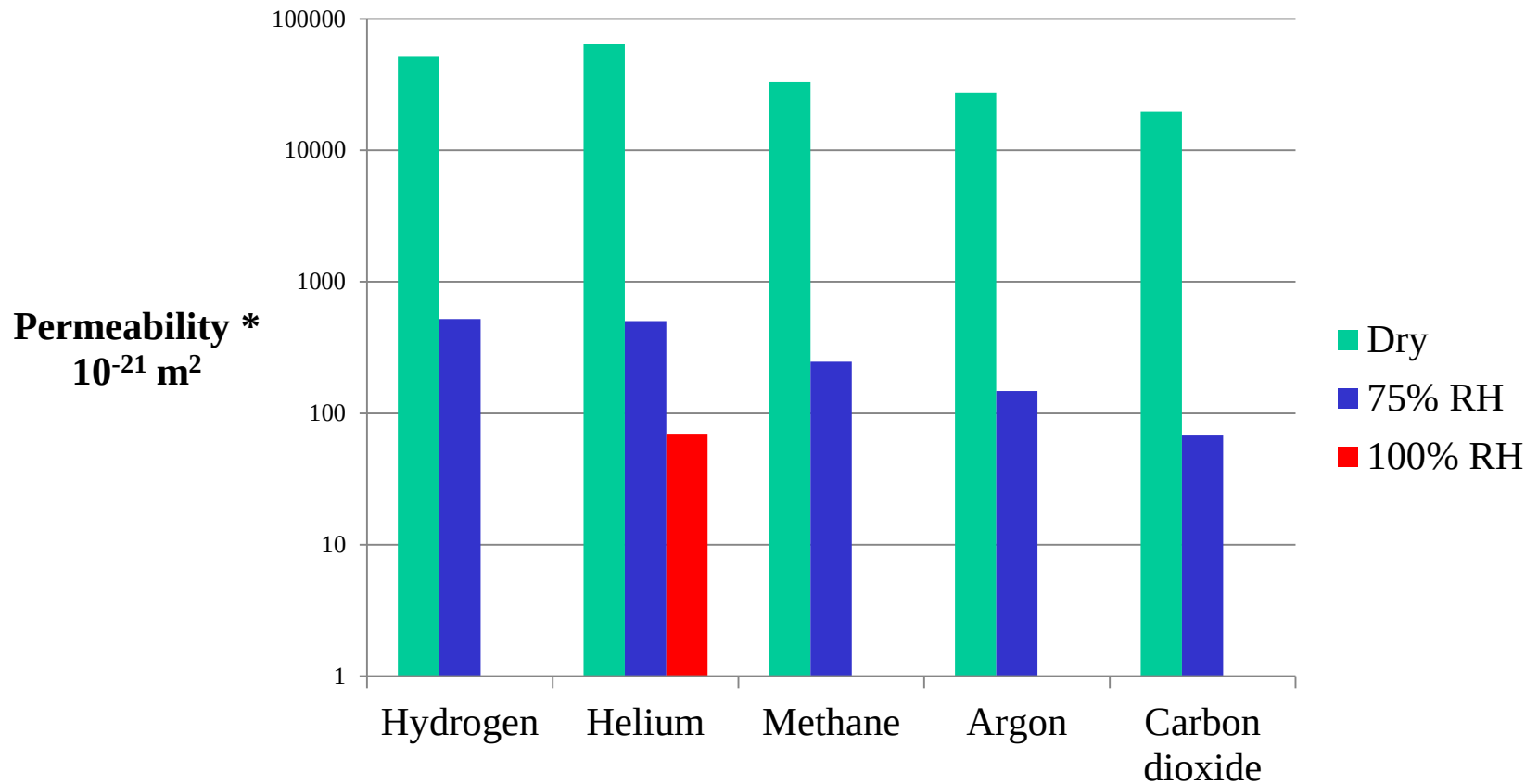


Surface tests using vacuum

Air Permeability Near Surface and Figg tests

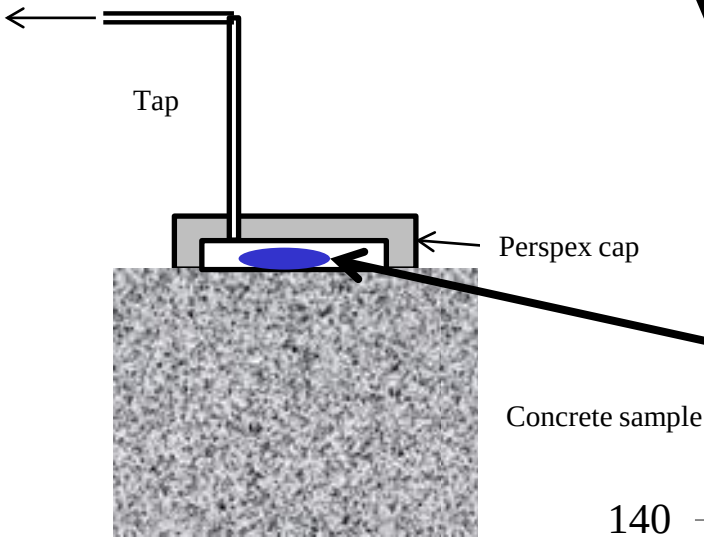


Effect of humidity on gas permeability



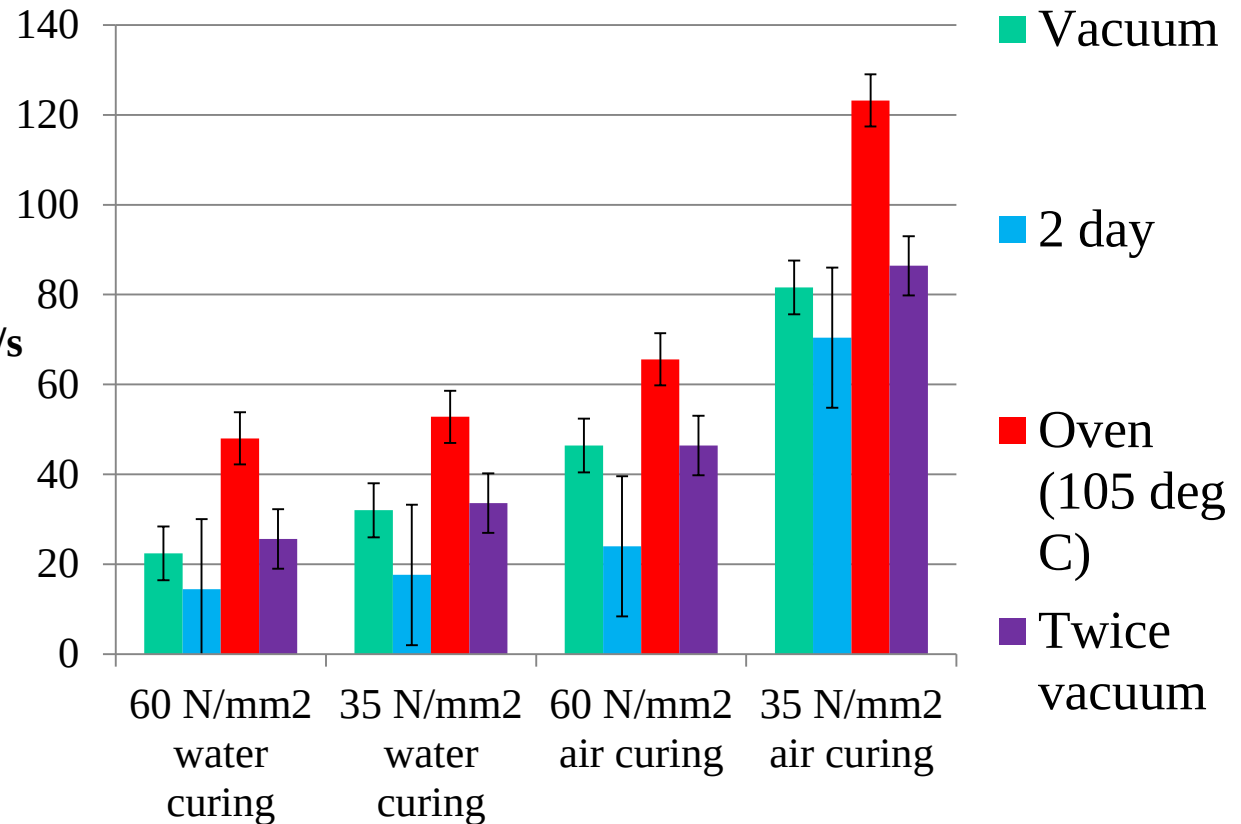
To vacuum pump

Vacuum Preconditioning



Vacuum applied until
silica gel turns blue

**ISA at 10
minutes
 $\times 10^{-2} \text{ ml/m}^2/\text{s}$**



Choosing a test

- The water tests are more sensitive to concrete permeability than the gas tests
- No clear advantage of either drilled hole or surface tests
- The tests measure different properties in that the water tests measure capillary suction as well as permeability
- If possible, a site test programme should use more than one test

Analytical solutions for the tests

- ISAT
$$F = A \left(\frac{Ks\varepsilon}{re} \right)^{1/2} t^{-1/2}$$

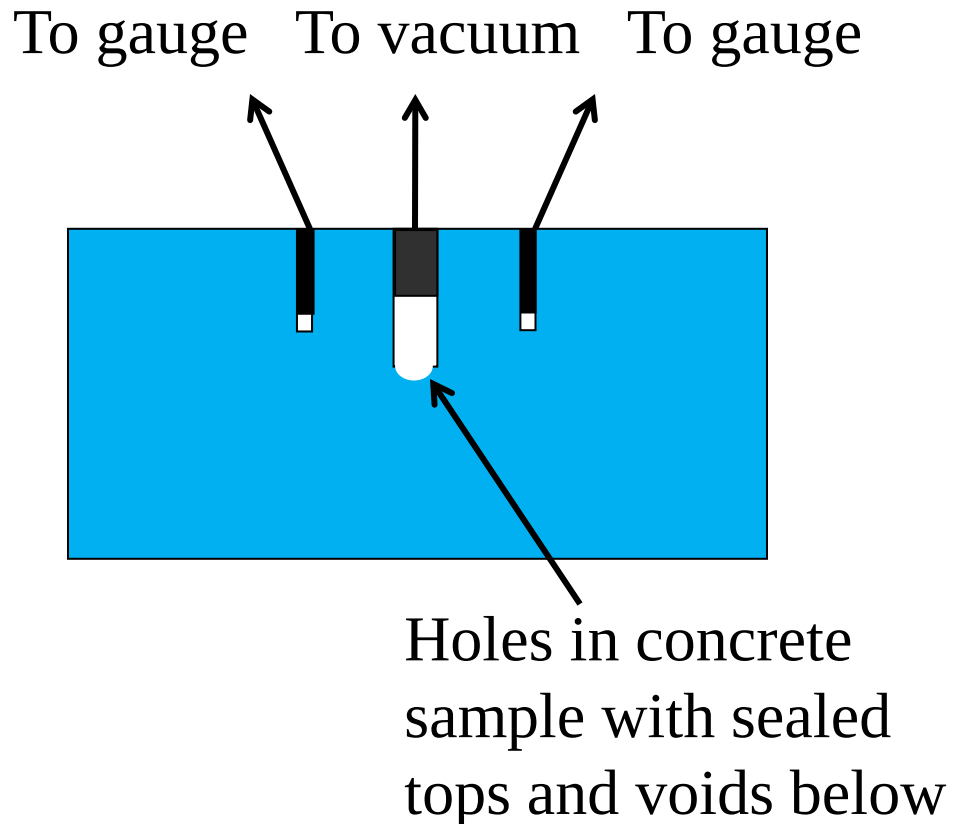
- The permeability K can be calculated

- Figg
$$K = \frac{ex_0^2}{2P_a \Delta t \left[\frac{1}{\ln\left(\frac{X}{x_0}\right)} - \frac{1}{L\left(\frac{1}{X_s} - \frac{1}{x_0}\right)} \right]} \ln\left(\frac{(55 \times 10^3 + P_a)(45 \times 10^3 - P_a)}{(55 \times 10^3 - P_a)(45 \times 10^3 + P_a)}\right)$$

- The permeability cannot be calculated without knowing the distance X over which the pressure drops

Measuring gas permeability requires more than one hole in the concrete

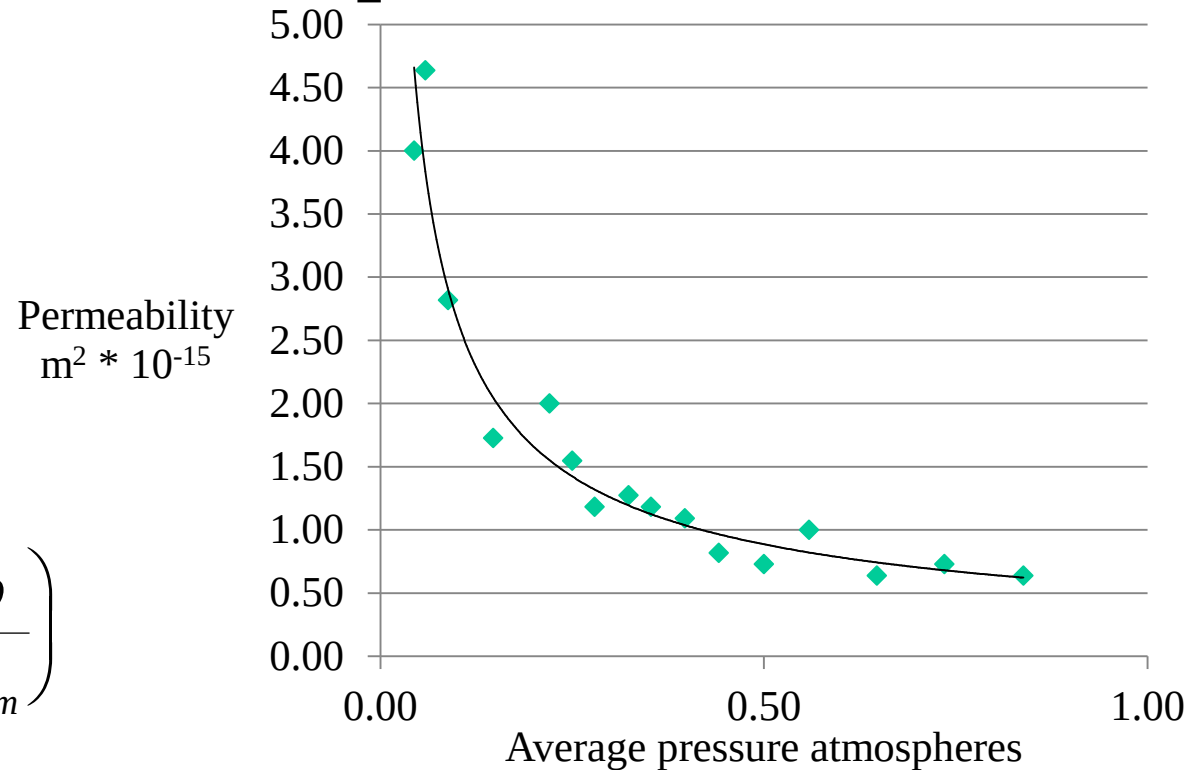
Apply a vacuum to the centre hole and monitor the pressure in the side holes



The Klinkenberg equation:

At low pressures gas permeability varies with pressure

$$K_l = \frac{K_g}{\left(1 + \frac{b}{P_m}\right)}$$

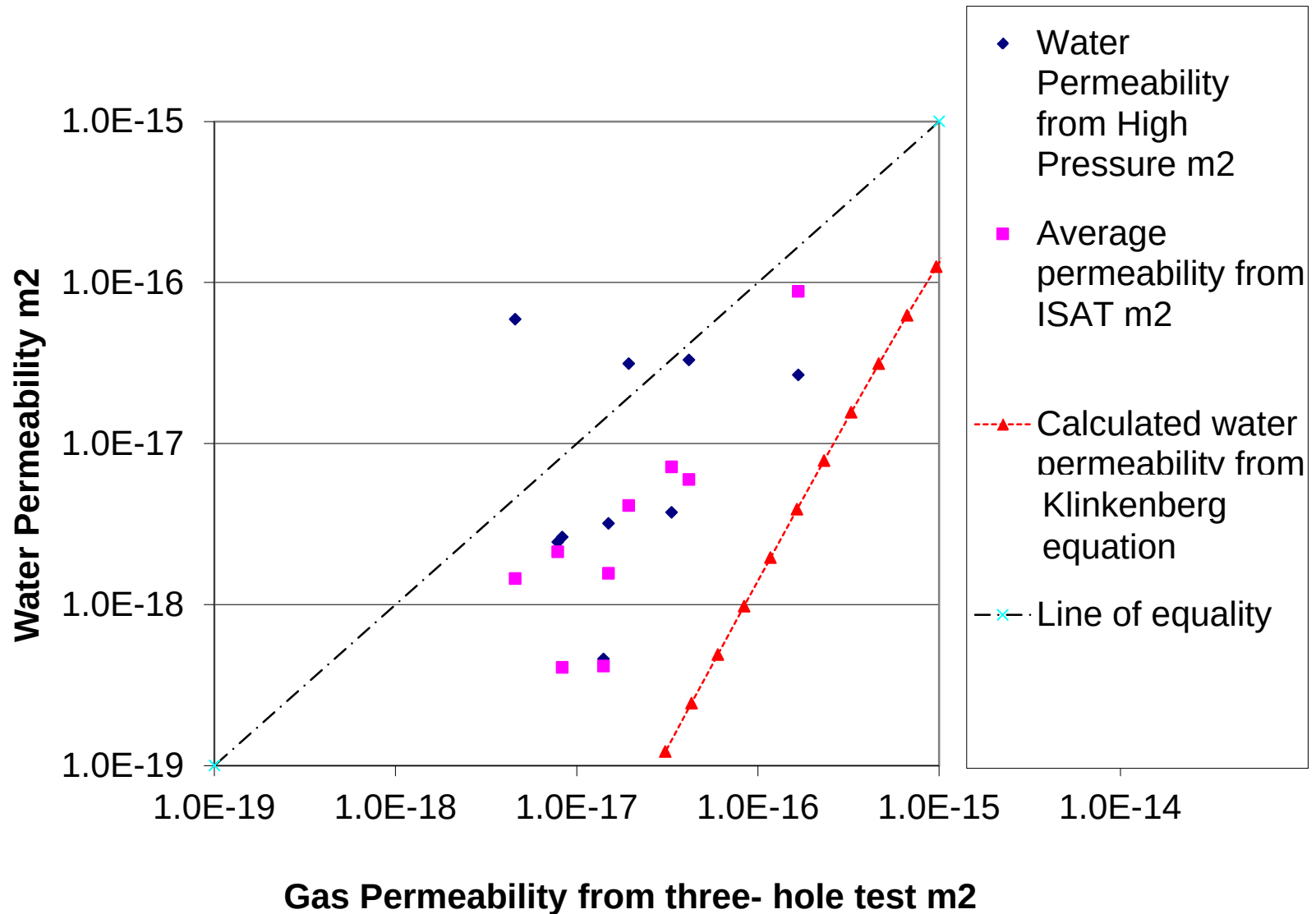


K_l = Water intrinsic permeability of concrete

K_g = Gas intrinsic permeability of concrete

P_m = The mean pressure at which gas is flowing

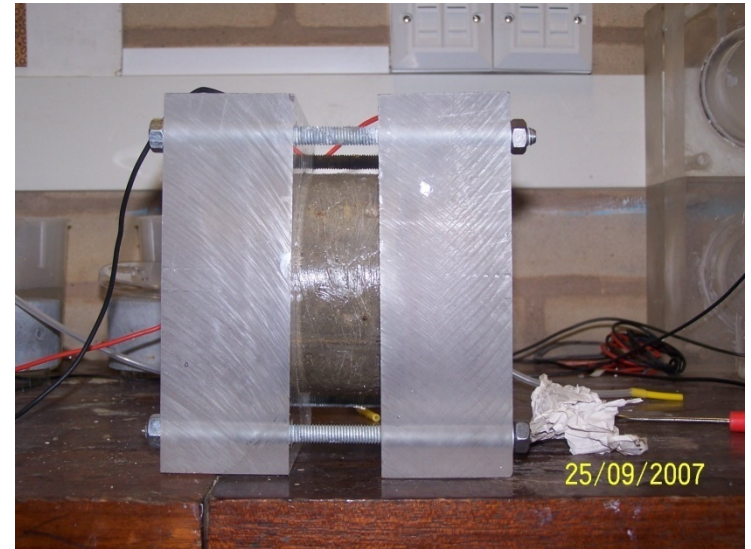
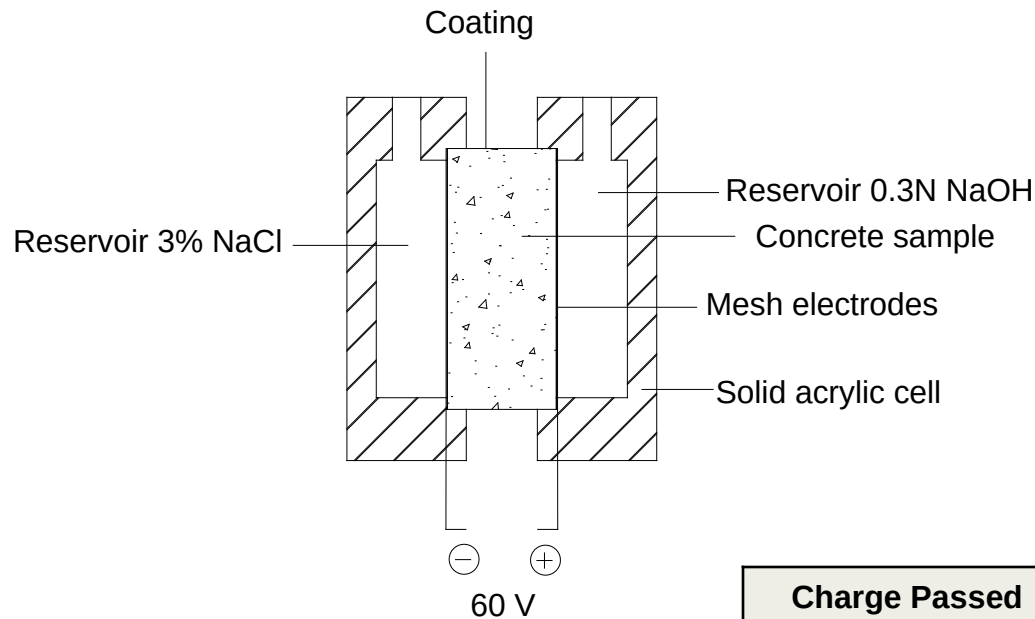
Comparison of permeabilities



Transport Properties of Concrete: Measurement and applications

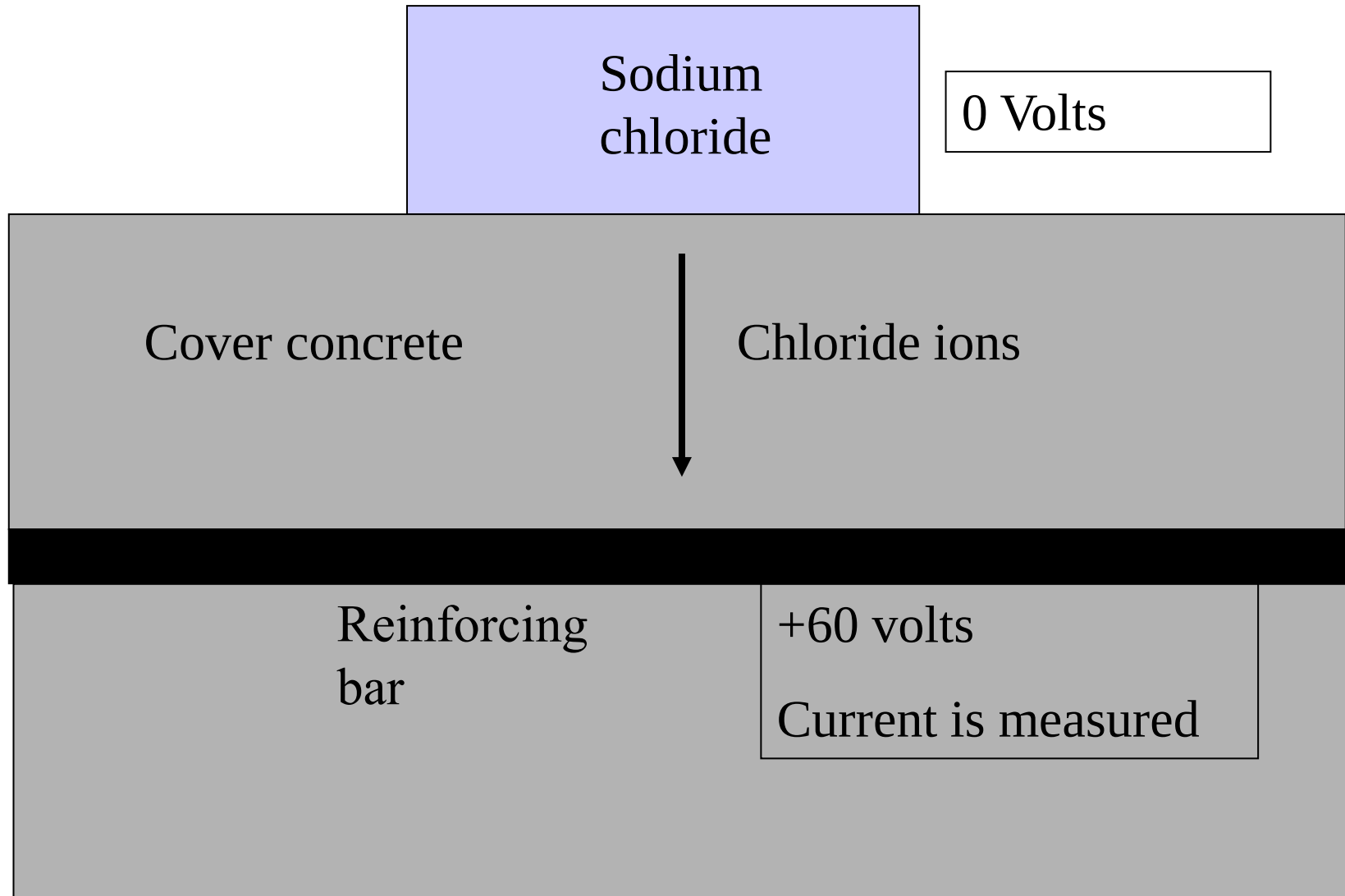
- The transport processes
- Processes which promote or inhibit transport
- Surface permeability tests
- Electrical tests
 - The “Rapid Chloride test”
 - Modelling ion-ion interactions
 - The Nordtest
 - Simple diffusion test (current control)
- Application of the results

ASTM C1202: Rapid Chloride Penetration Test (RCPT)



Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000 - 4,000	Moderate
1,000 - 2,000	Low
100 - 1,000	Very low
<100	Negligible

The insitu version of the rapid chloride test



Solving the hard way –

assuming E is constant

$$i = AFD_{cl}c_s \left[\frac{1}{\sqrt{\pi D_{cl}t}} e^{\frac{(x-aD_{cl}t)^2}{4D_{cl}t}} + \frac{a}{2} \operatorname{erfc}\left(\frac{x-aD_{cl}t}{2\sqrt{D_{cl}t}}\right) \right]$$

Where $a = \frac{zFE}{RT}$

This gives a solution for diffusion and electromigration of a single ion but it takes no account of ion-ion interactions so computer modelling must be used.

The Progress of a Chloride Ion



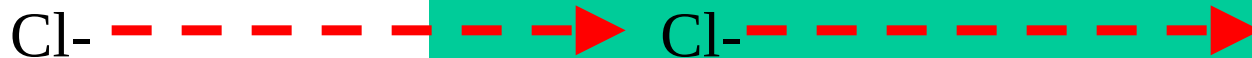
A Chloride ion enters the sample... what happens next?



Either the ion is adsorbed – forms chloroaluminate.

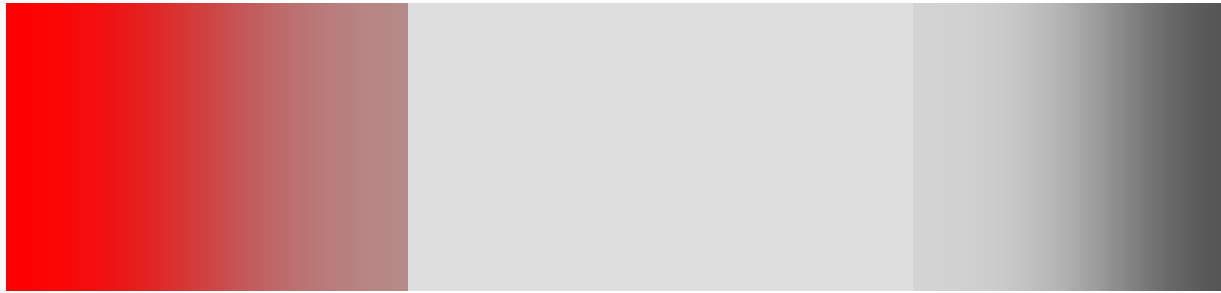


or it stops because the concentration gradient falls
making it less mobile than the OH^-



or it carries on

Section through sample during test

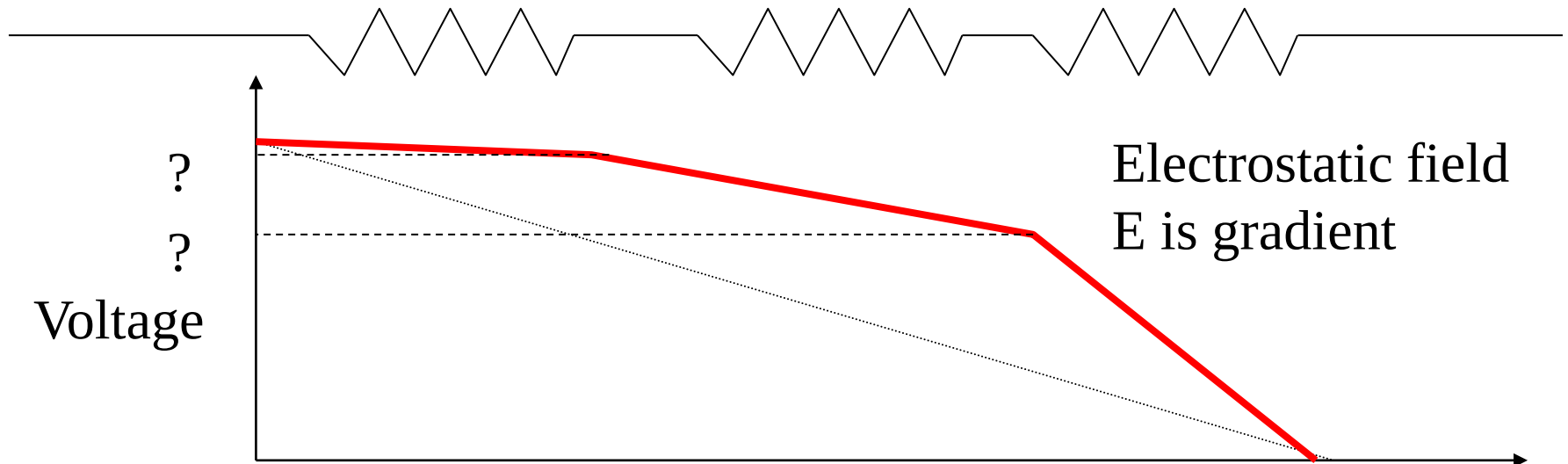


Chloride zone

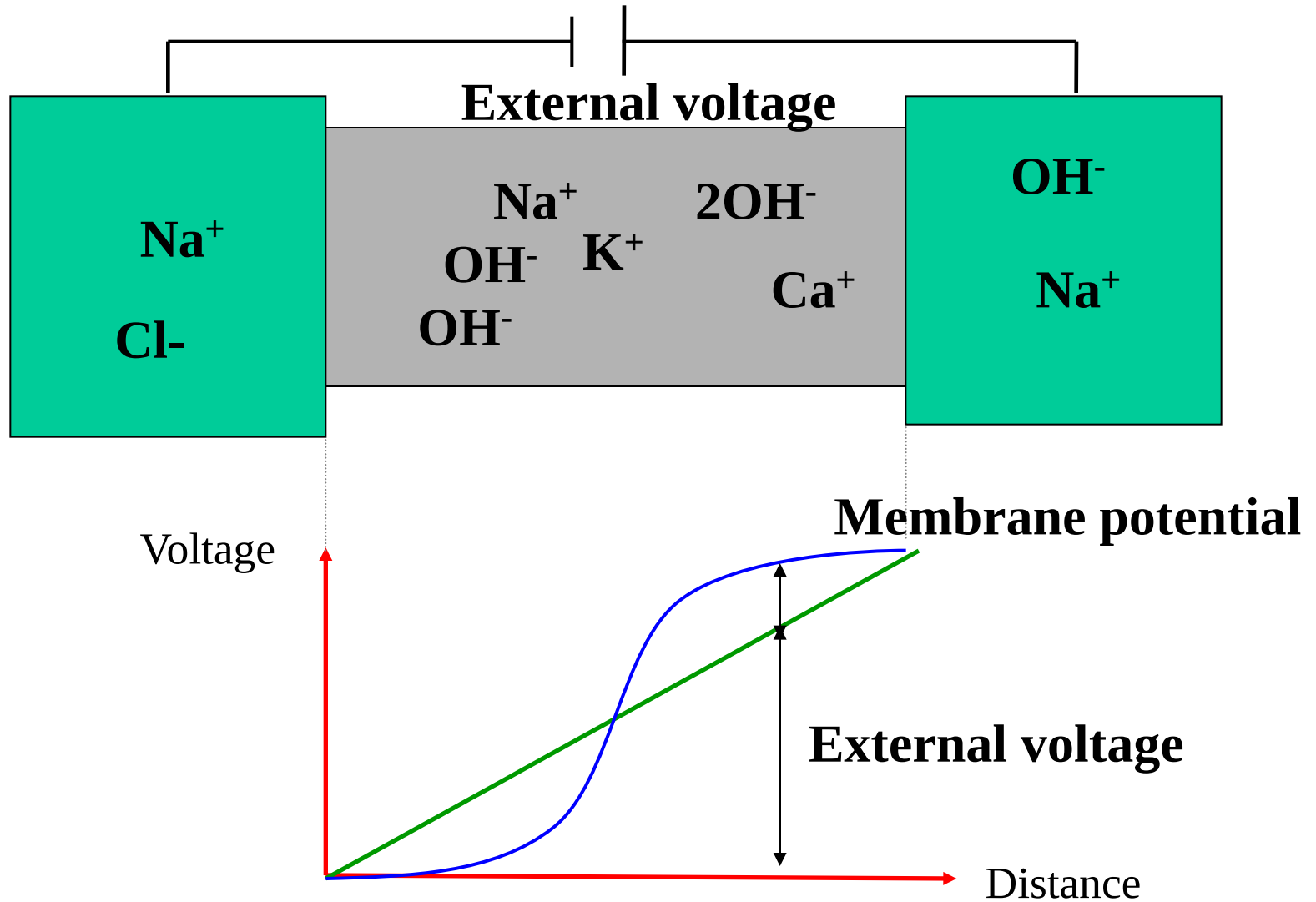
Sodium zone

Low resistance (high D)

High resistance (low D)

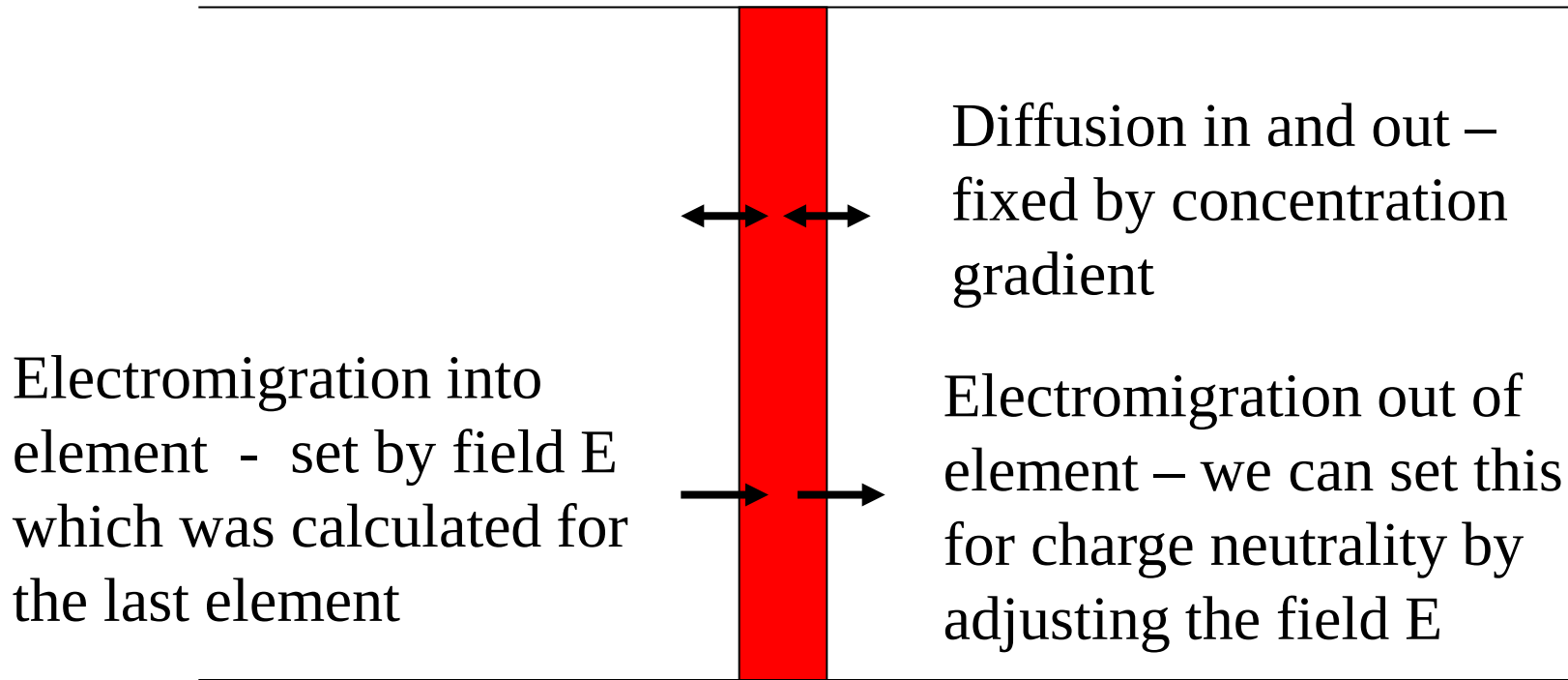


Membrane Potential



Modelling a thin slice of the sample for a short time step

Apply Kirchoff's law : current in = current out

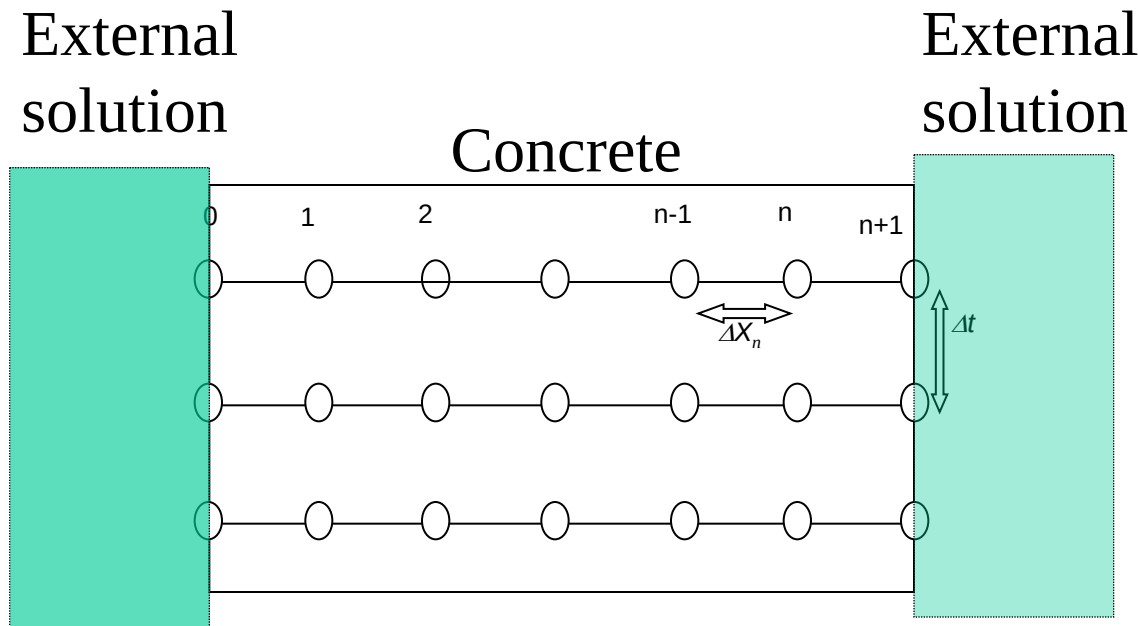


Final adjustments are needed to get the correct total voltage across the sample.

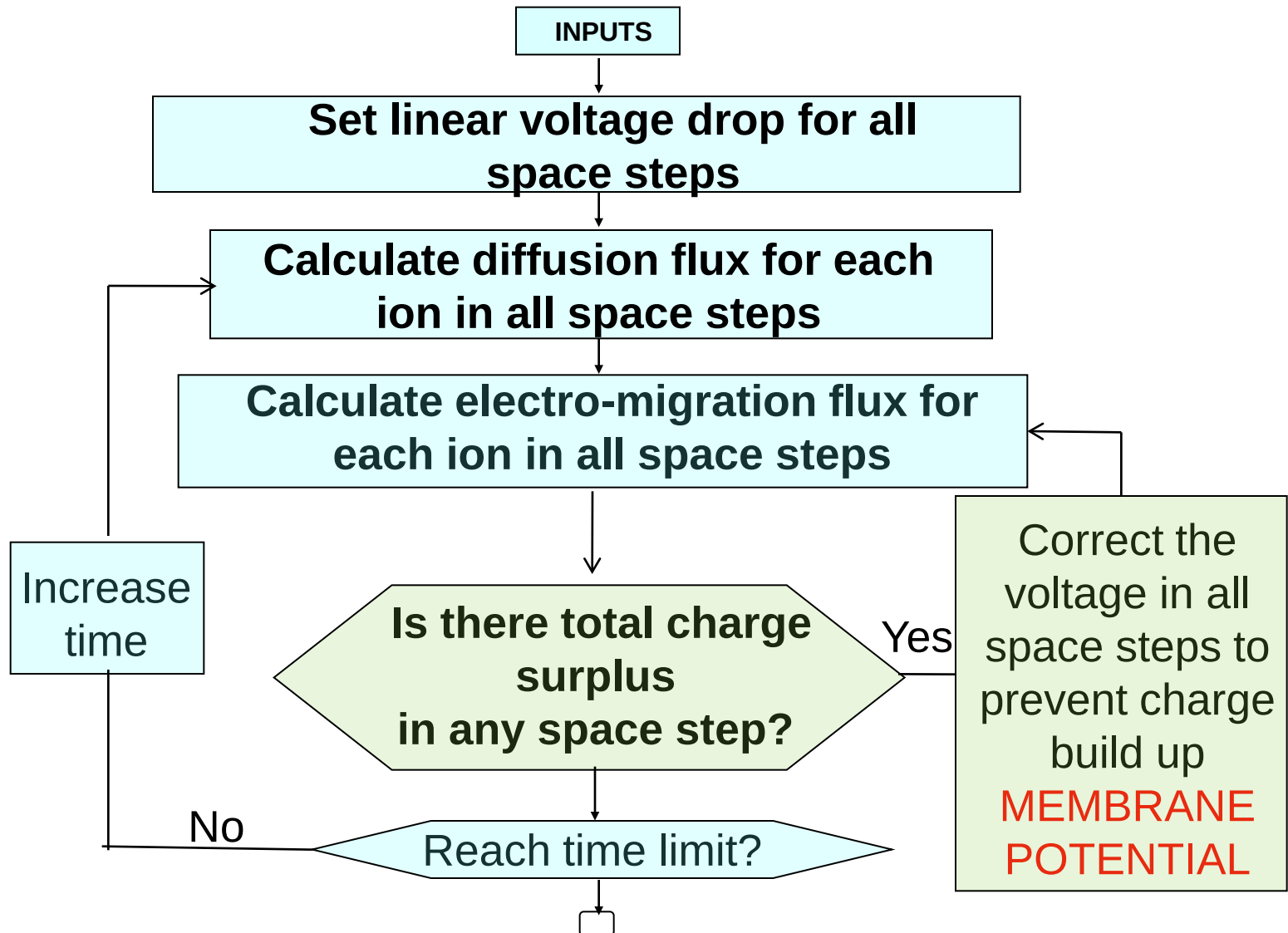
Electro-diffusion model for chlorides

- **Nernst-Planck equation:**
$$J_i = \underbrace{D_i \frac{\partial c_i}{\partial x}}_{\text{Diffusion}} + \underbrace{\frac{z_i F}{RT} D_i c_i \frac{\partial E}{\partial x}}_{\text{Migration}}$$

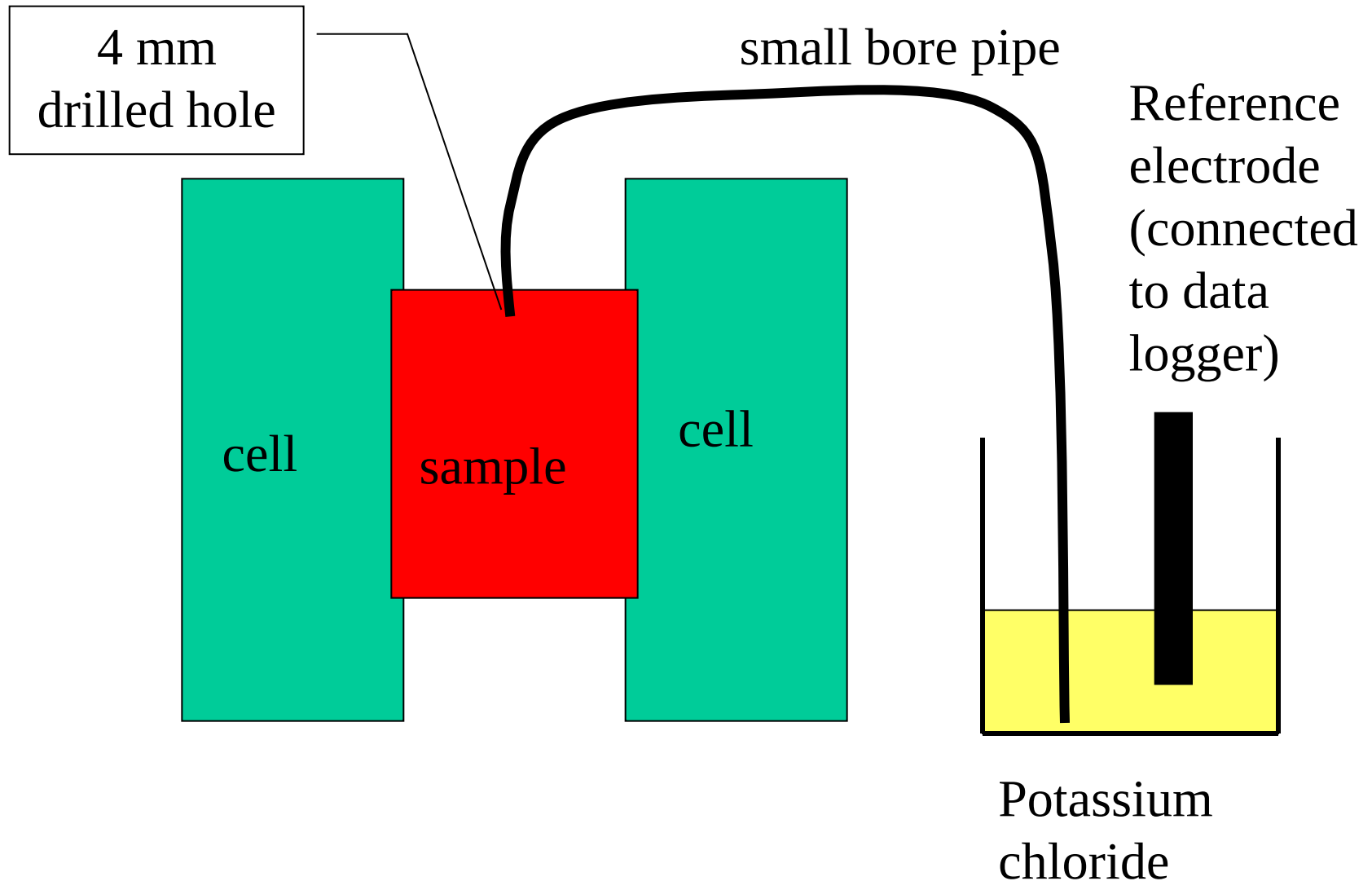
- **Charge electroneutrality (Kirchoff's law):**
$$0 = F \sum_i z_i J_i$$



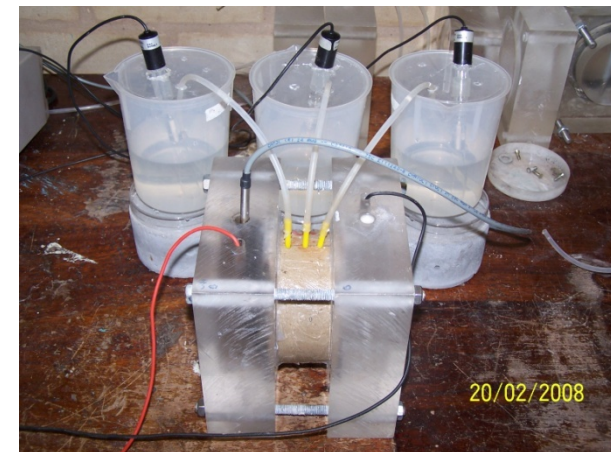
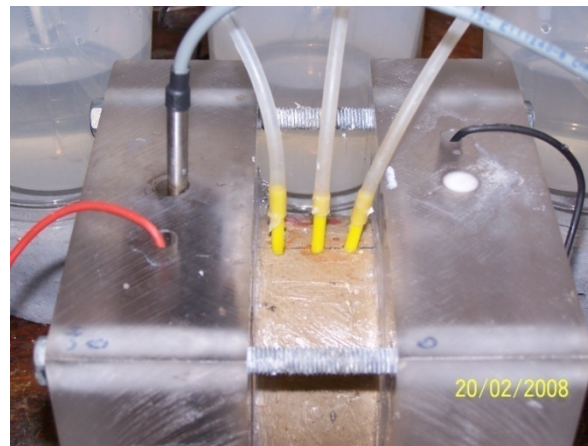
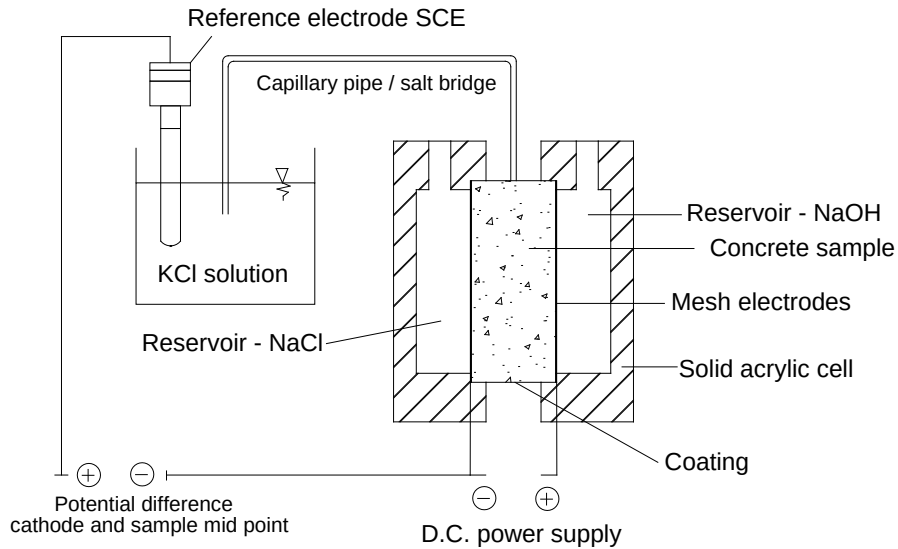
Key elements of the computer code



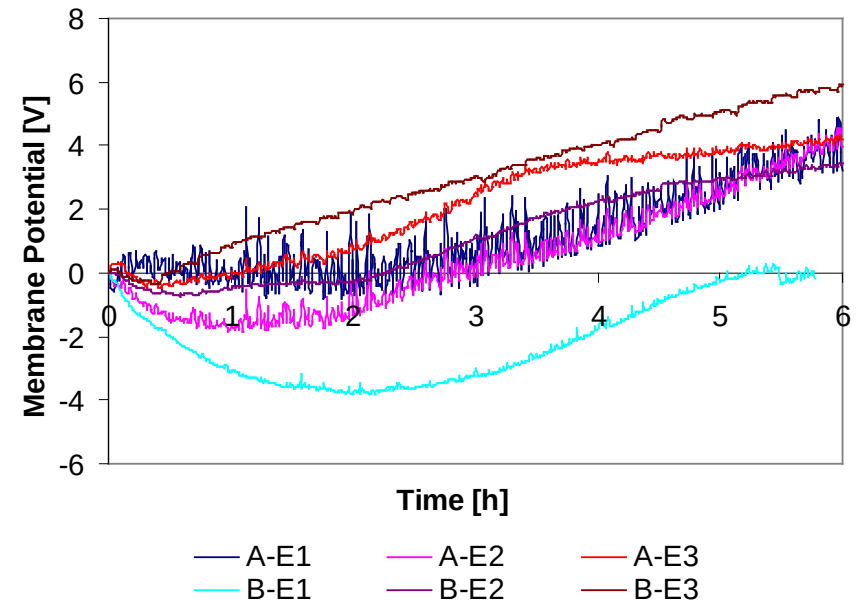
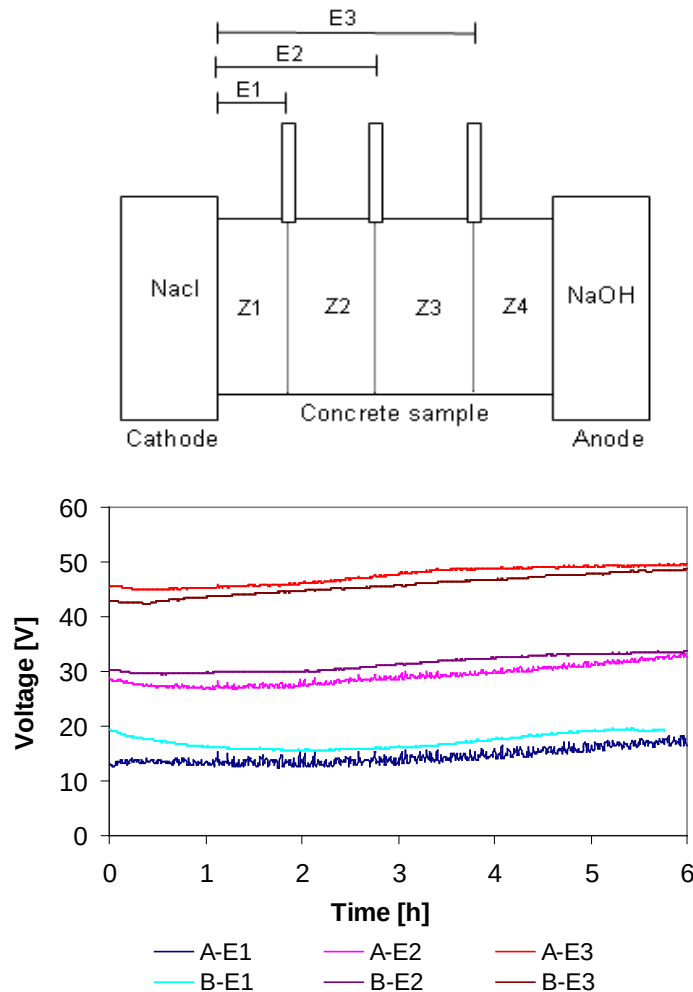
Checking the model – Salt bridge measurements



Salt Bridge Apparatus



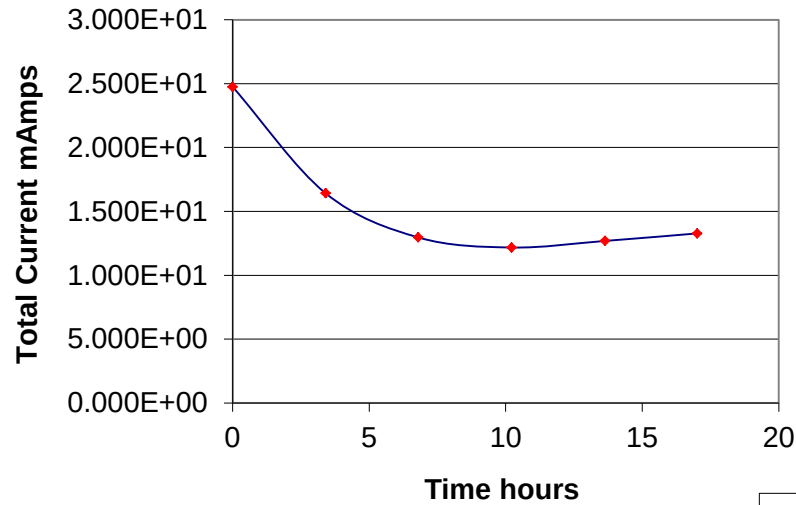
Results from salt bridge



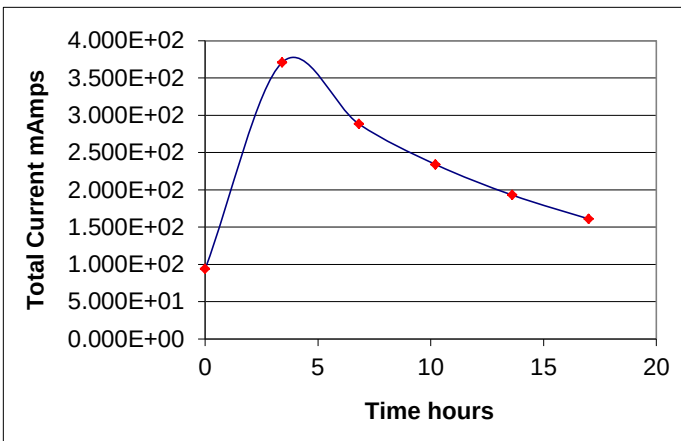
Membrane Potential: $\Delta V = V_n - V_o$

Experimental data

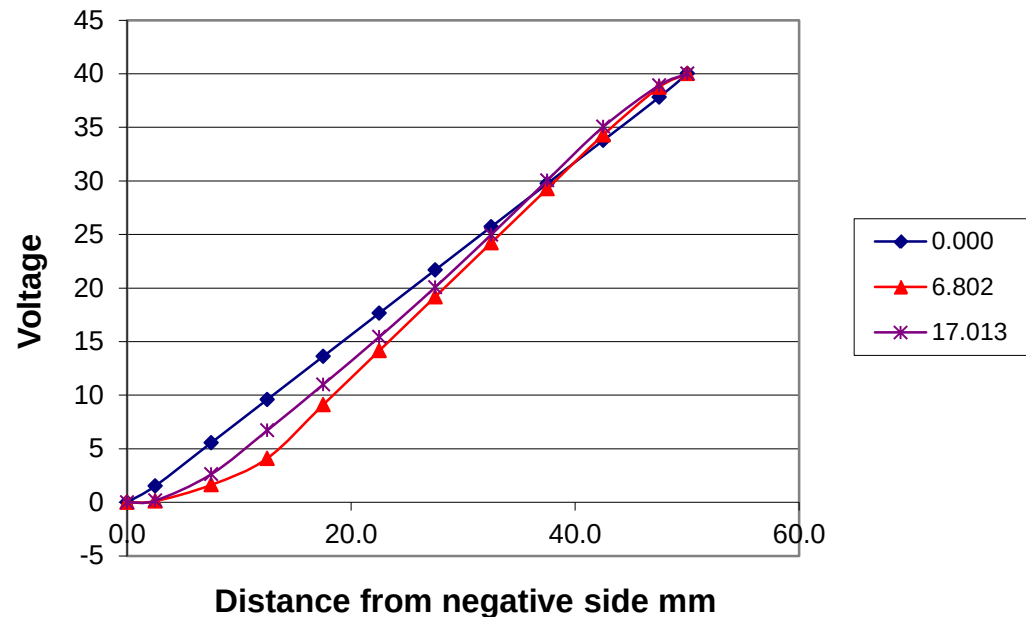
Model output for current and voltage



Current vs time with no voltage correction (average)

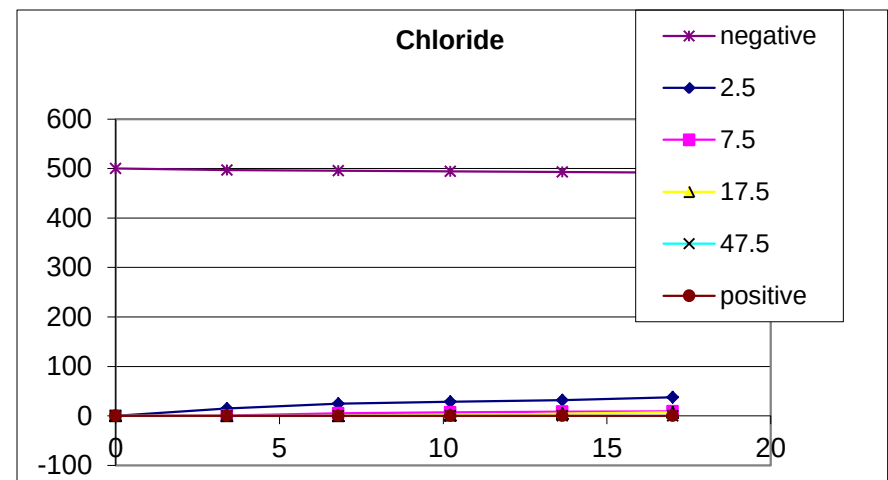
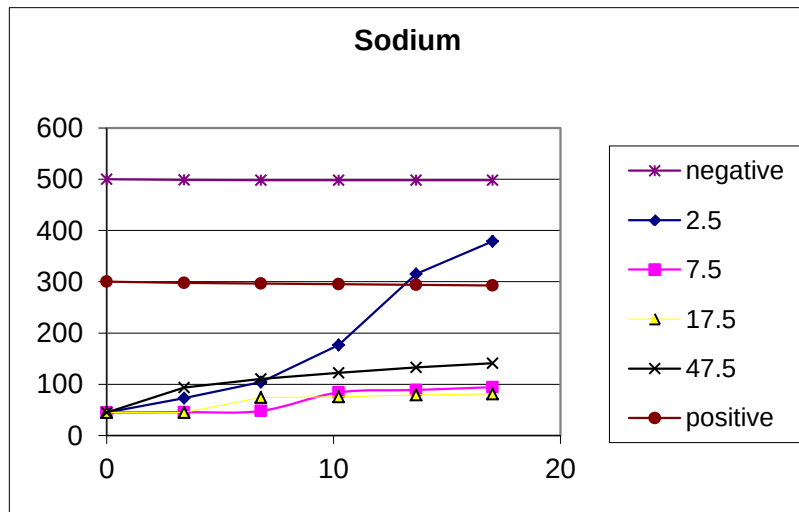
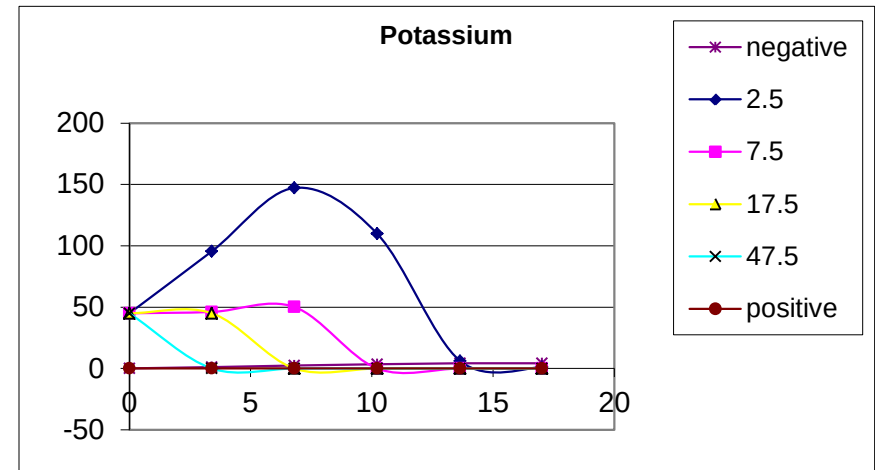
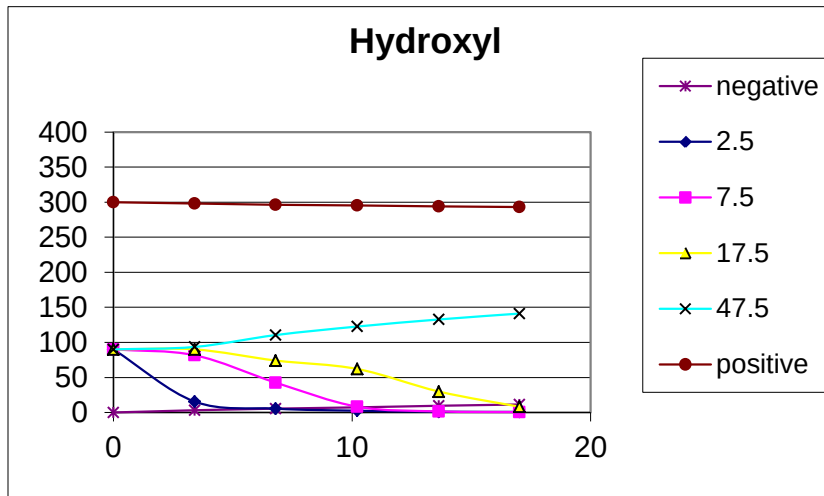


Voltage adjustments at different times

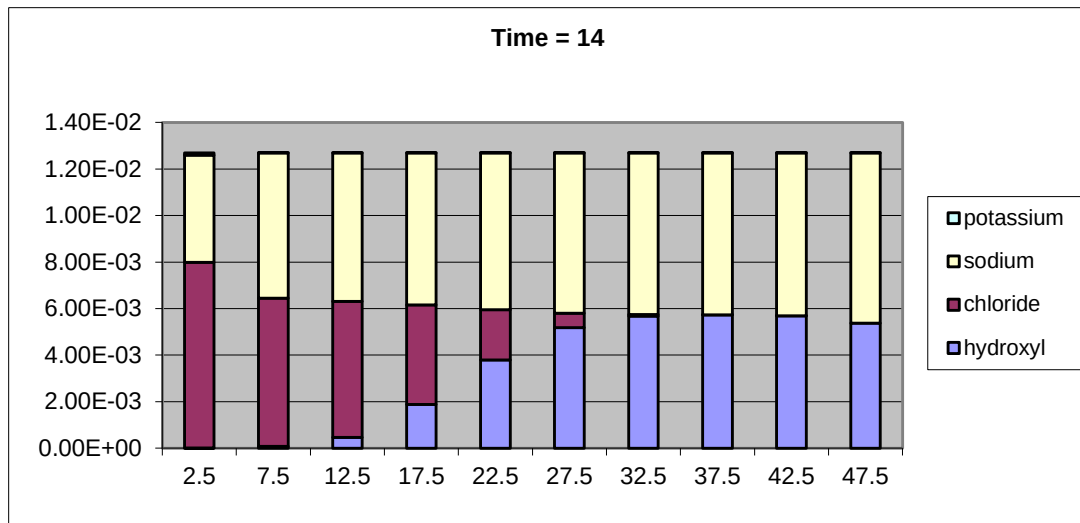
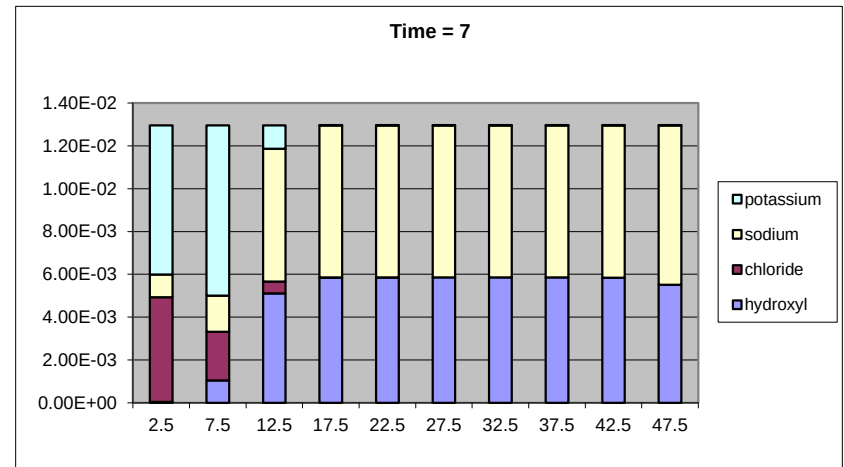
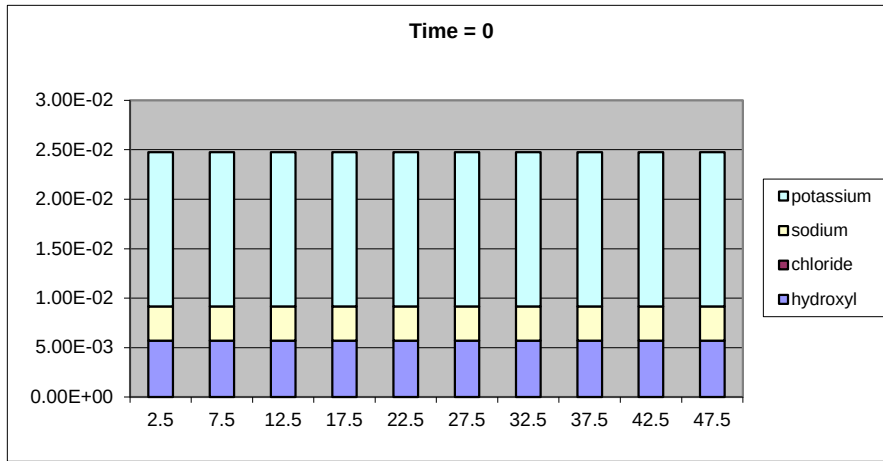


Concentrations in cells

at distances from negative side in mol/m³ vs time in hours



Current in amps at different times in hours vs position in mm from the negative side



Optimization Model

Transport properties

- Intrinsic diffusion coefficient (Cl^-)
- Intrinsic diffusion coefficient (OH^-)
- Intrinsic diffusion coefficient (Na^+)
- Intrinsic diffusion coefficient (K^+)
- Porosity (ϵ)
- Chloride binding capacity factor (α)
- OH^- conc. of the pore solution

Data base

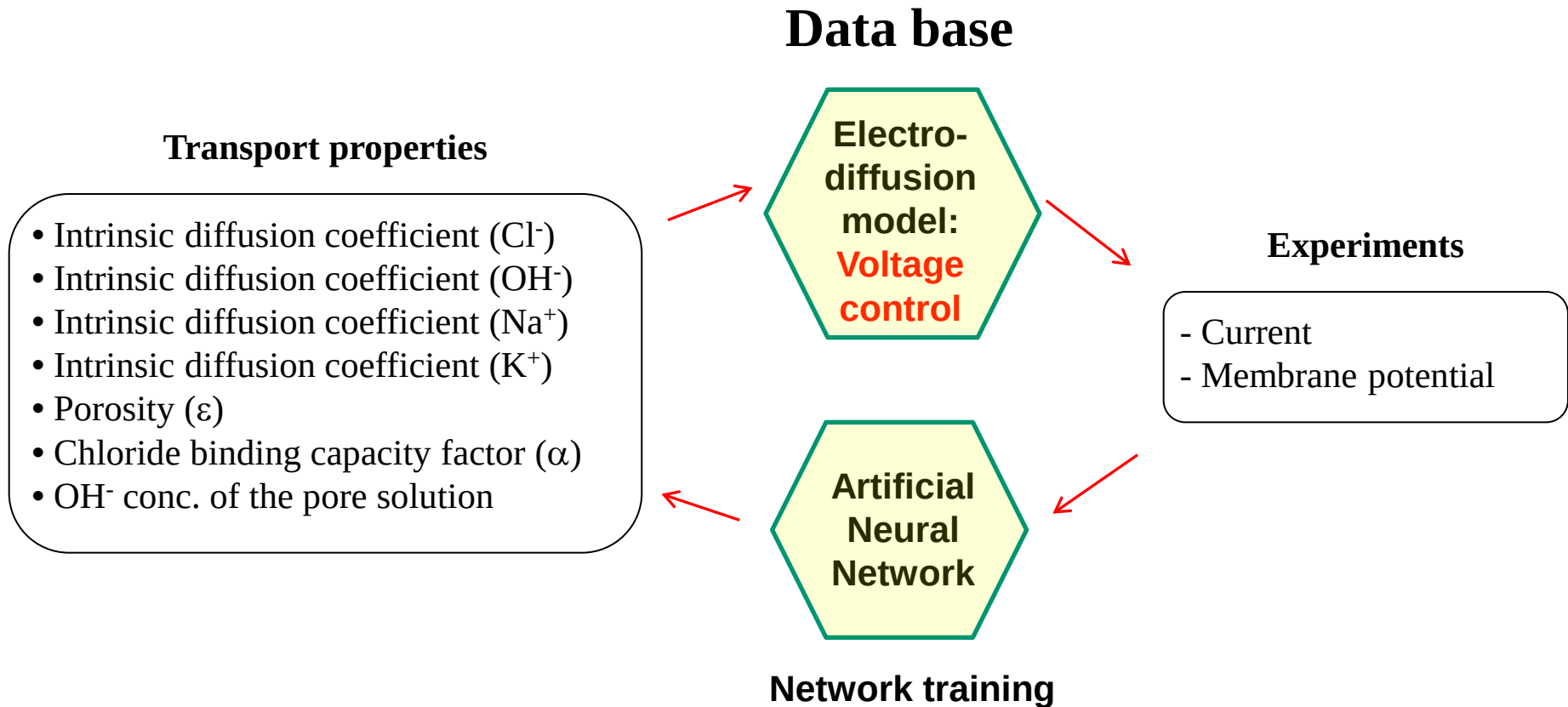
Electro-diffusion
model:
**Voltage
control**

Experiments

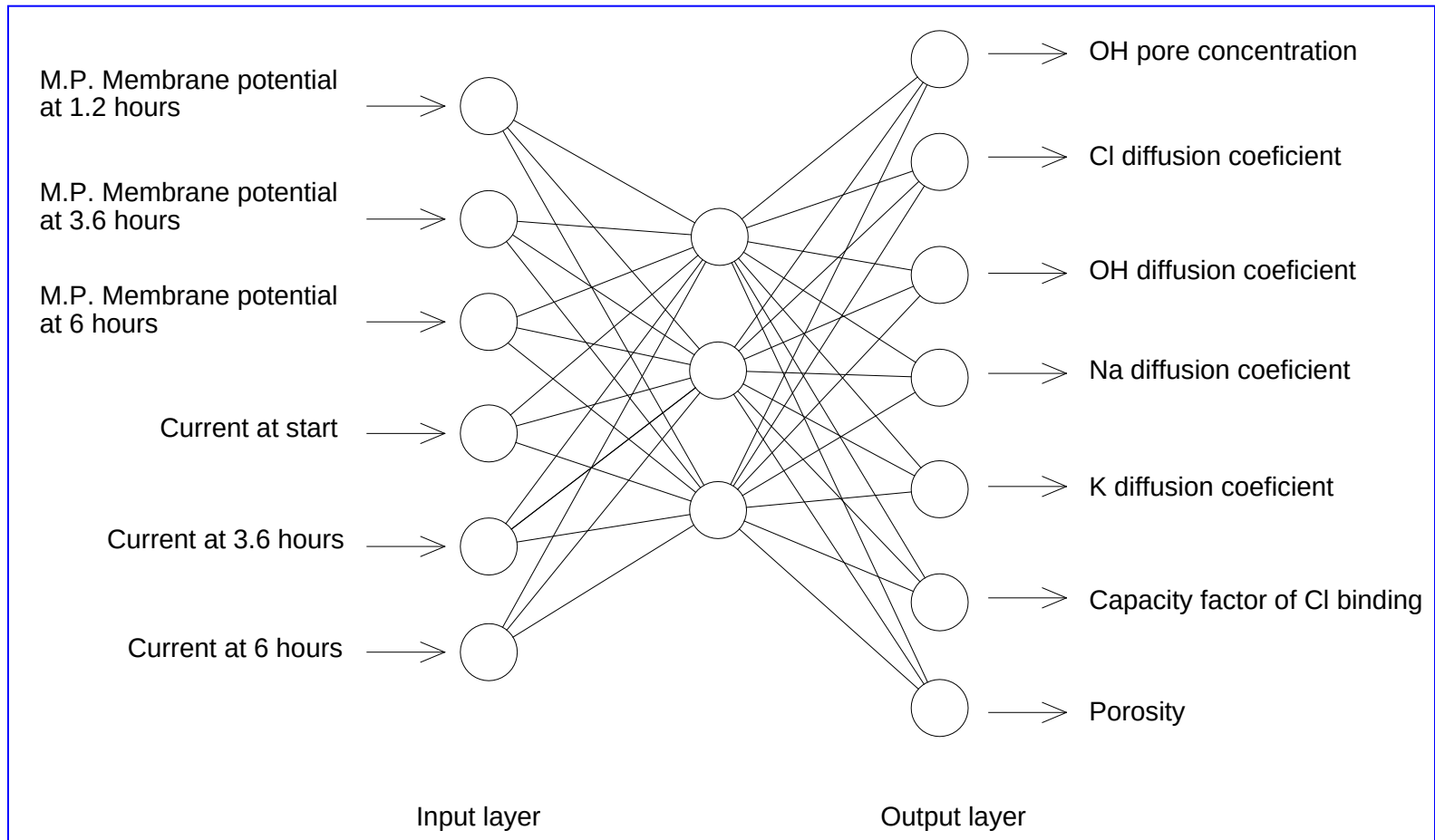
- Current
- Membrane potential

Artificial
Neural
Network

Network training

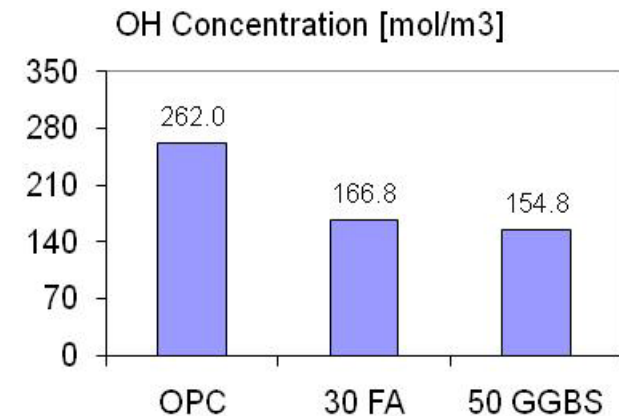
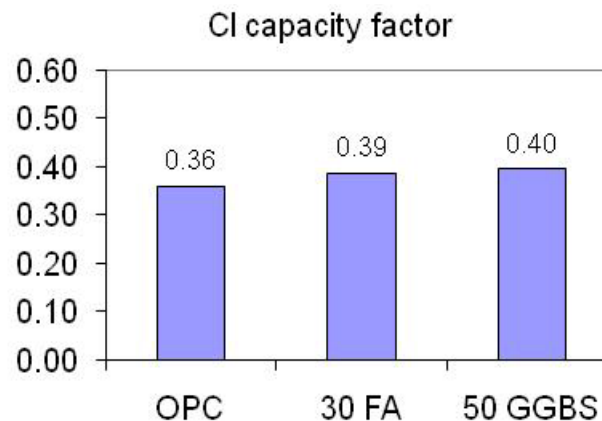
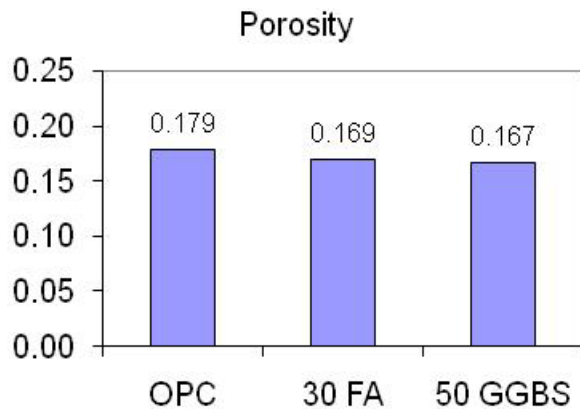
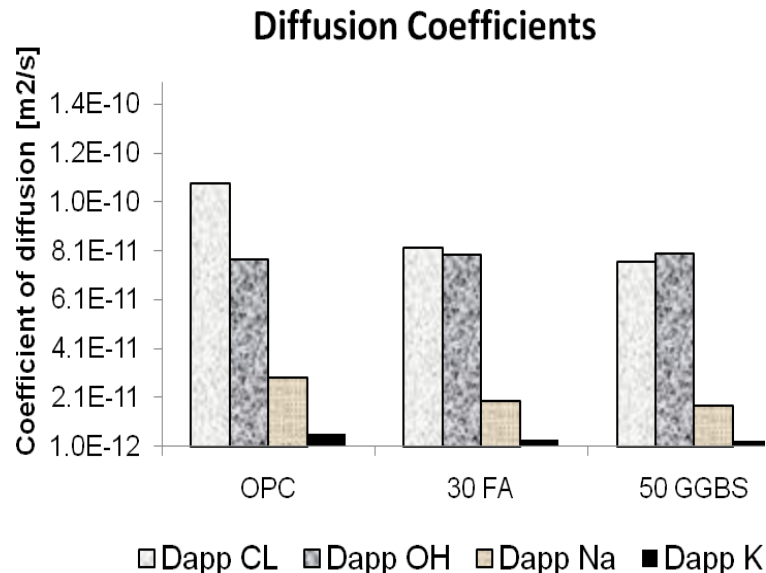


Artificial Neural Network



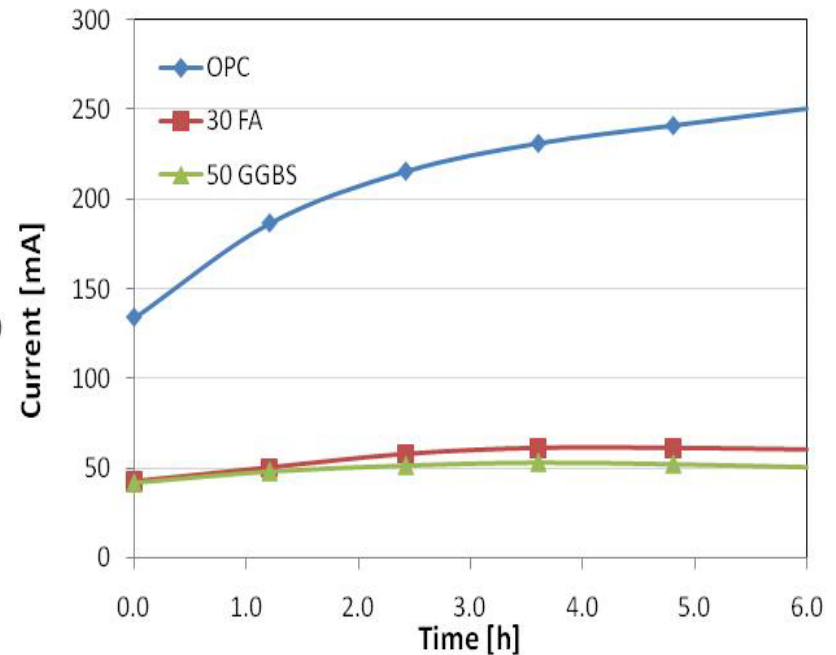
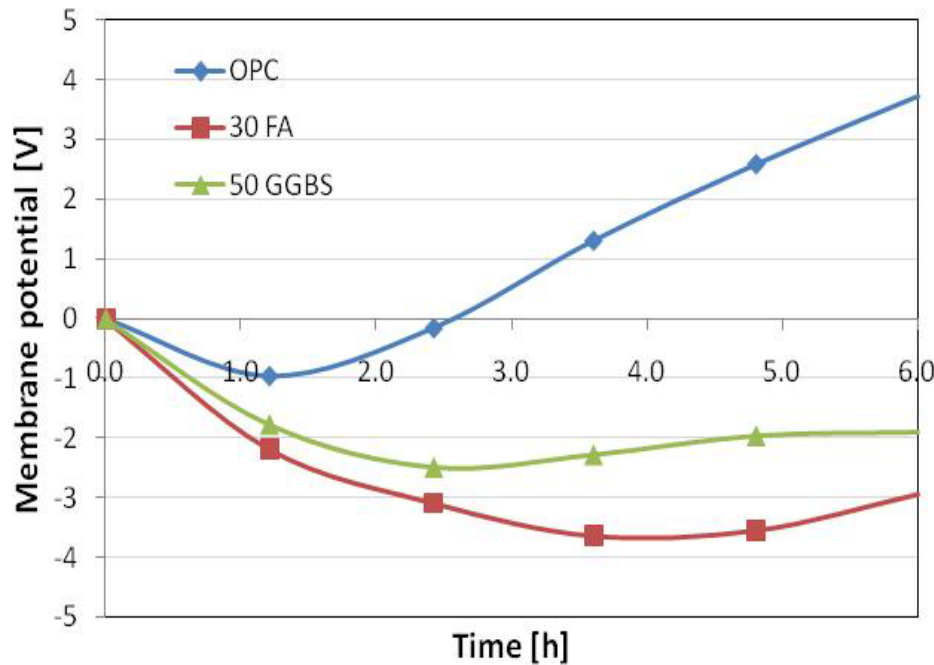
Chloride related properties

from experimental data used in the model



Comparing different mixes in the rapid chloride test.

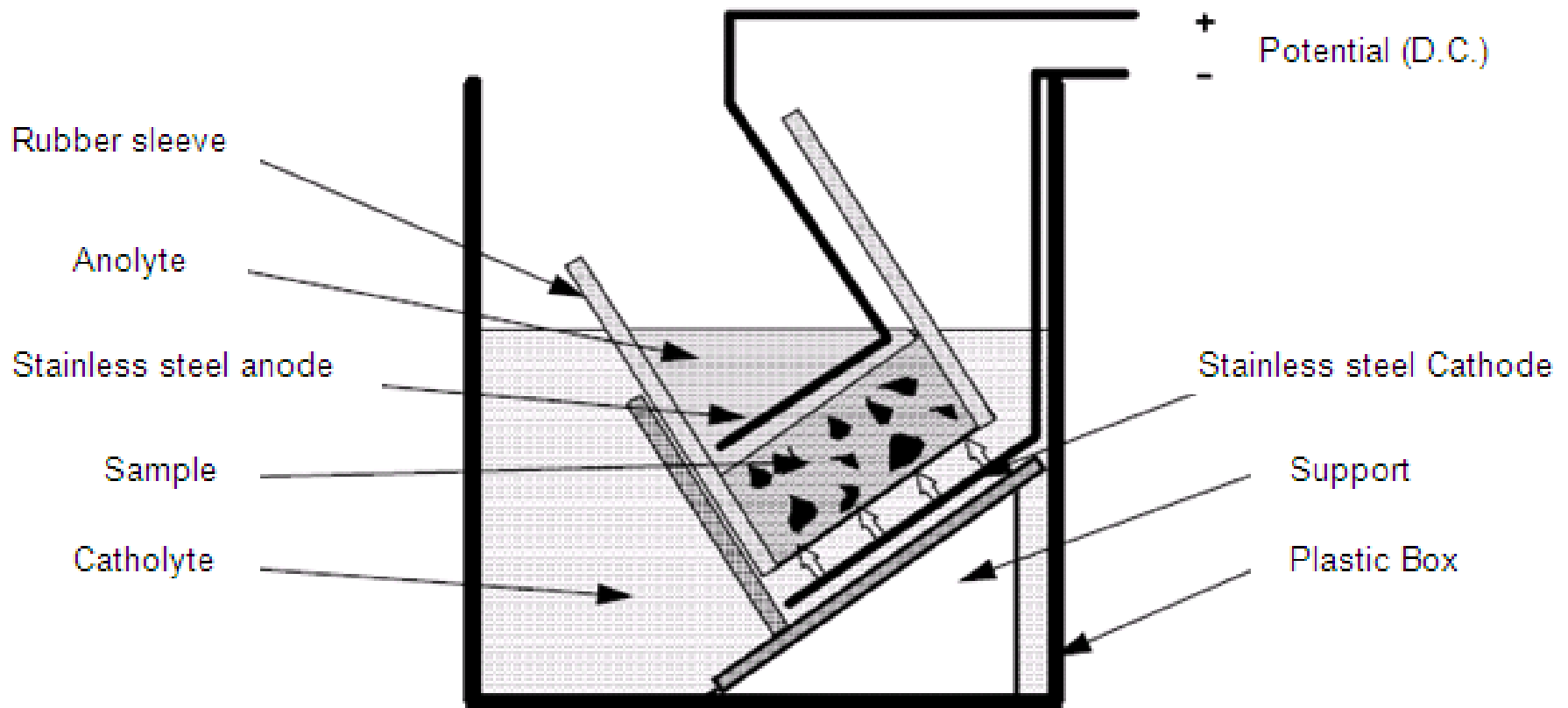
Membrane potential (left) and current vs. time (right)



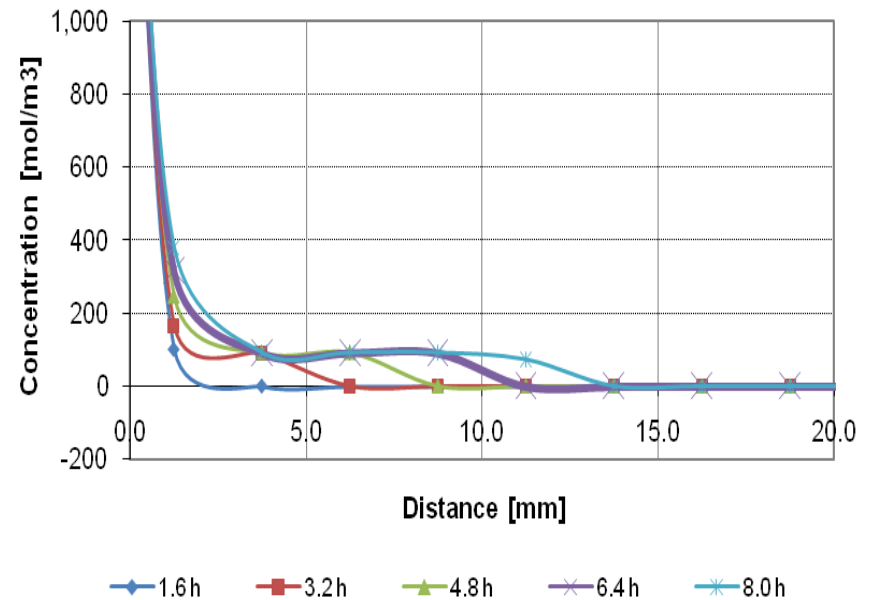
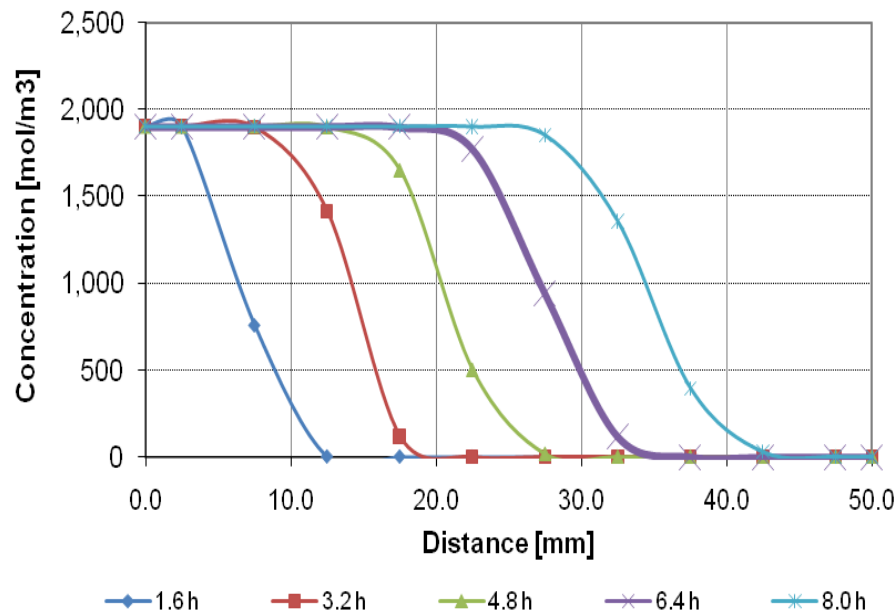
How to get more from the rapid chloride test

- Measure the mid-point voltage
- Measure the initial and final current as well as the average
- Run for as long as possible
- Keep the reservoirs small so they get depleted.

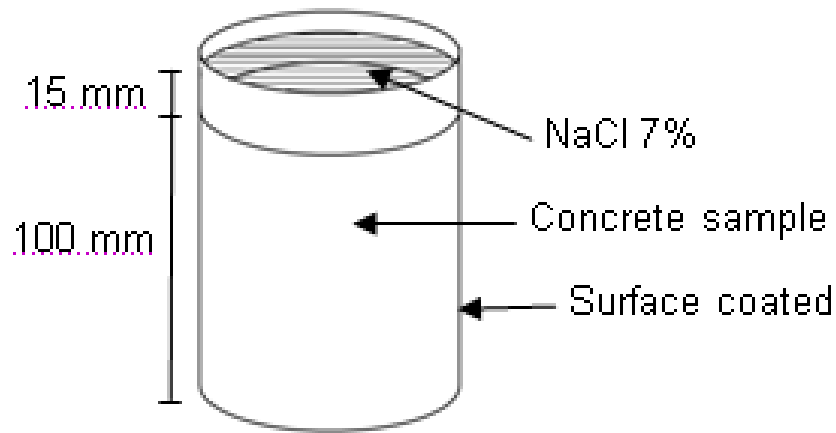
The Nordtest NT Build-492 Test



Modelling the Nordtest without ion-ion interactions (left) and with ion-ion interactions (right)



“Traditional” diffusion test



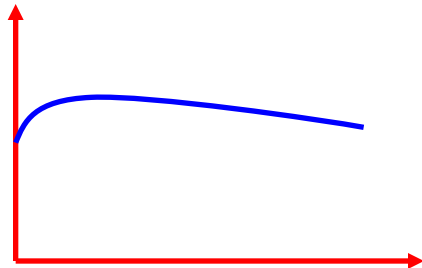
For modelling:

- The boundary condition is not zero voltage because the ends of the sample are not short-circuited.
- A voltage can be measured.
- The voltage in the model is set to give zero current.

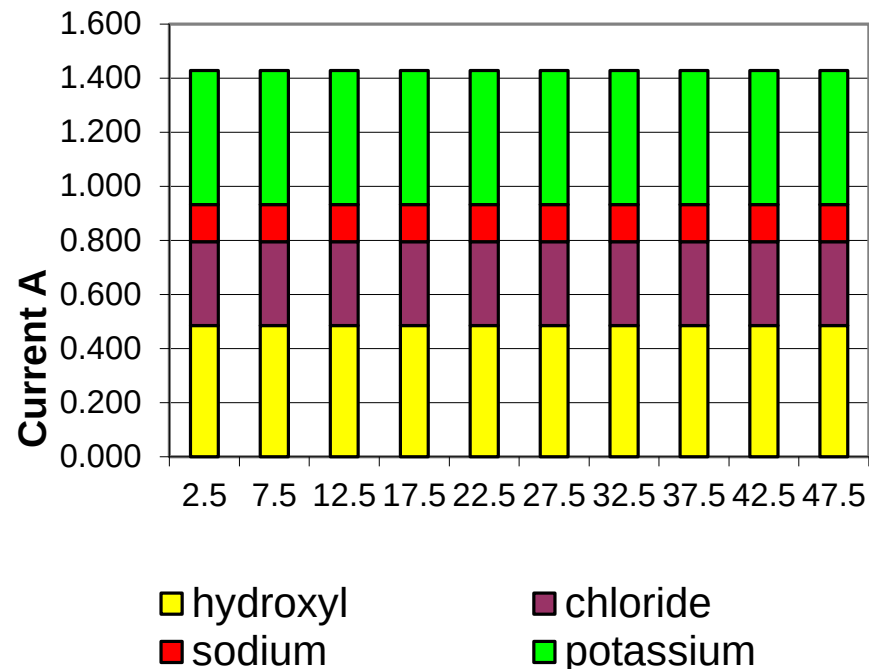
Voltage control model

- External voltage: fixed ($\neq 0$)
 - Membrane potential: calculated ($\neq 0$)
 - Total current: calculated ($\neq 0$)
- } Migration test

Total
current



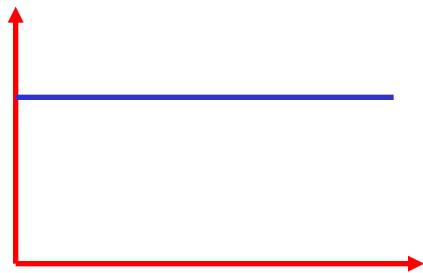
Time



Current control model (I)

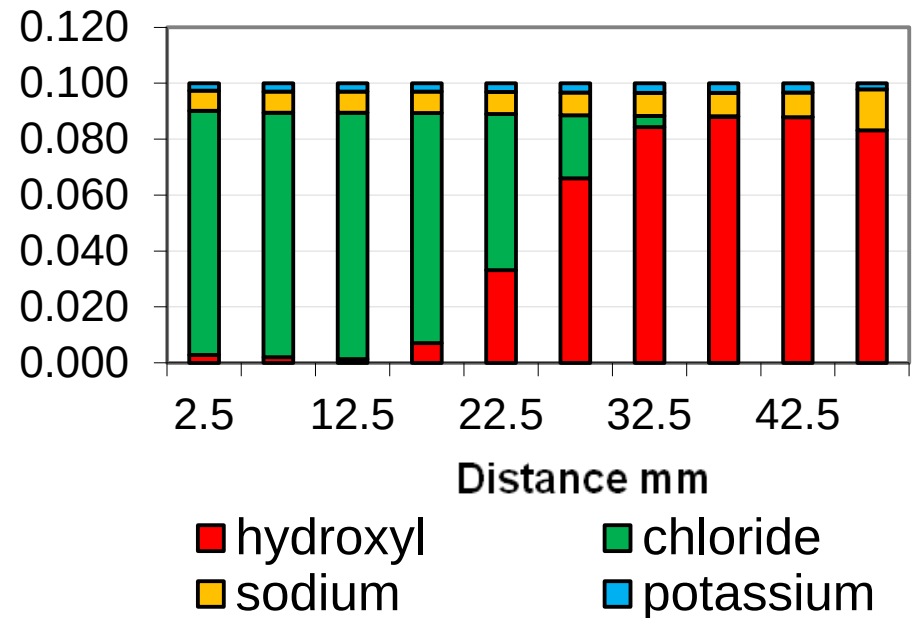
- External current: fixed ($\neq 0$)
 - Membrane potential: calculated ($\neq 0$)
 - Required voltage: calculated ($\neq 0$)
- } •Cathodic protection
•Electrochemical extraction

Total
current



Time

Current A



Current control model (II)

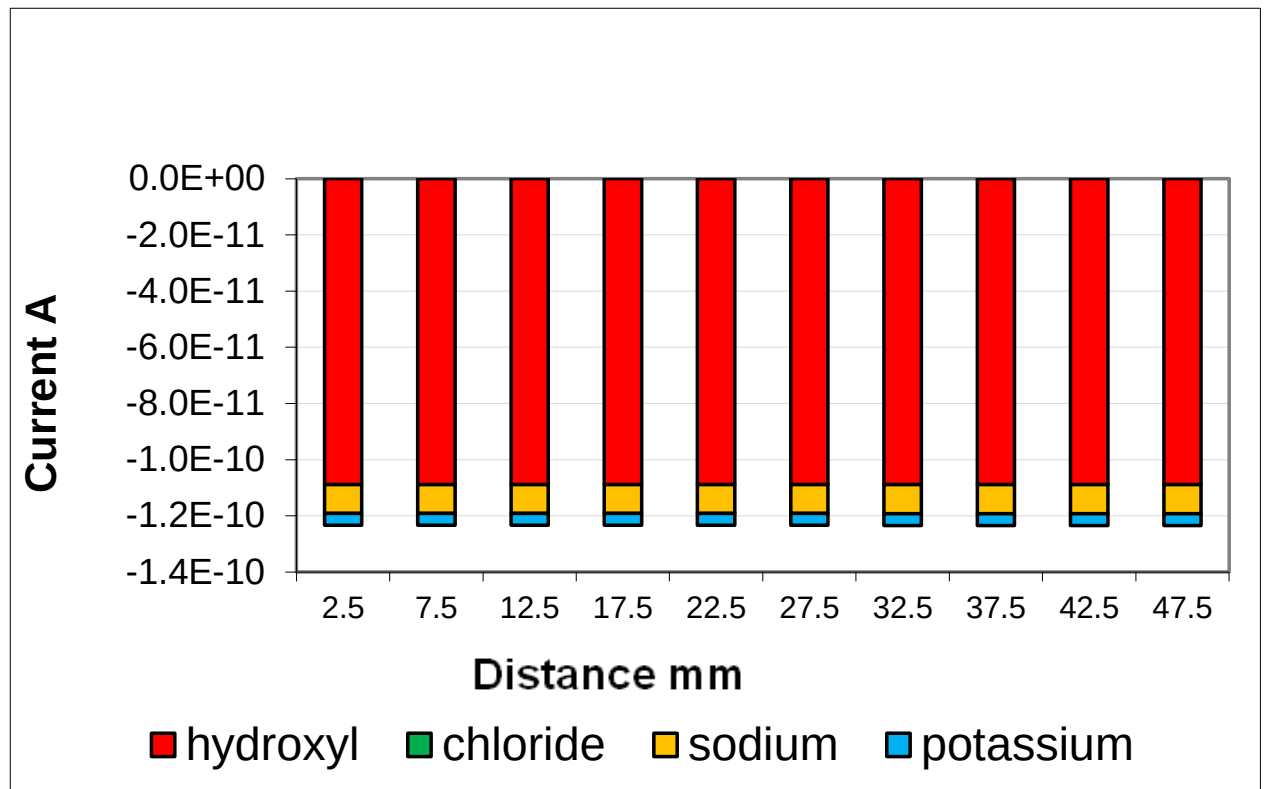
- External current: fixed ($=0$)
- Required voltage equal to membrane potential ($\neq 0$)

Self diffusion

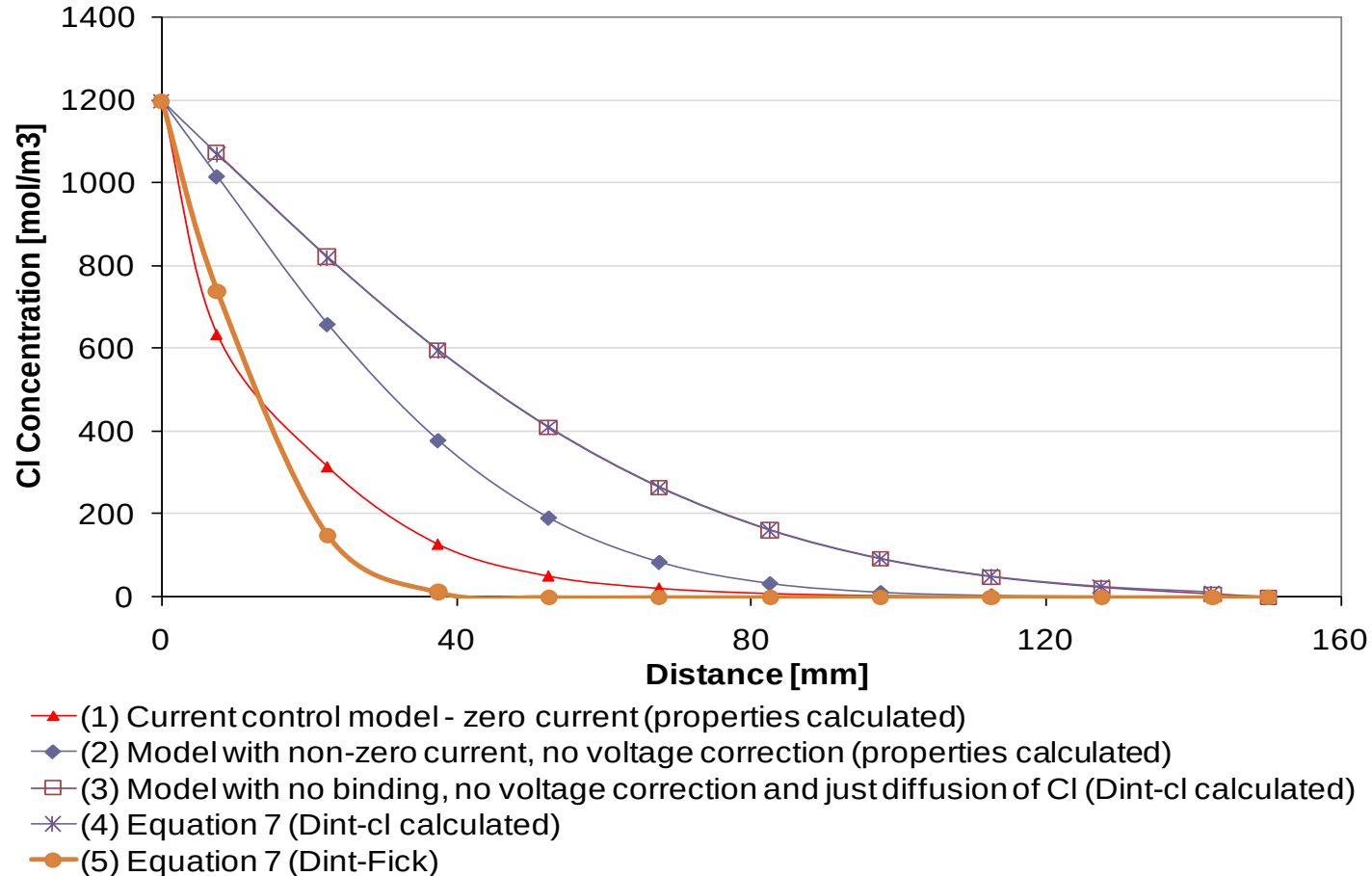
Total
current



Time



Traditional diffusion test (no applied voltage)



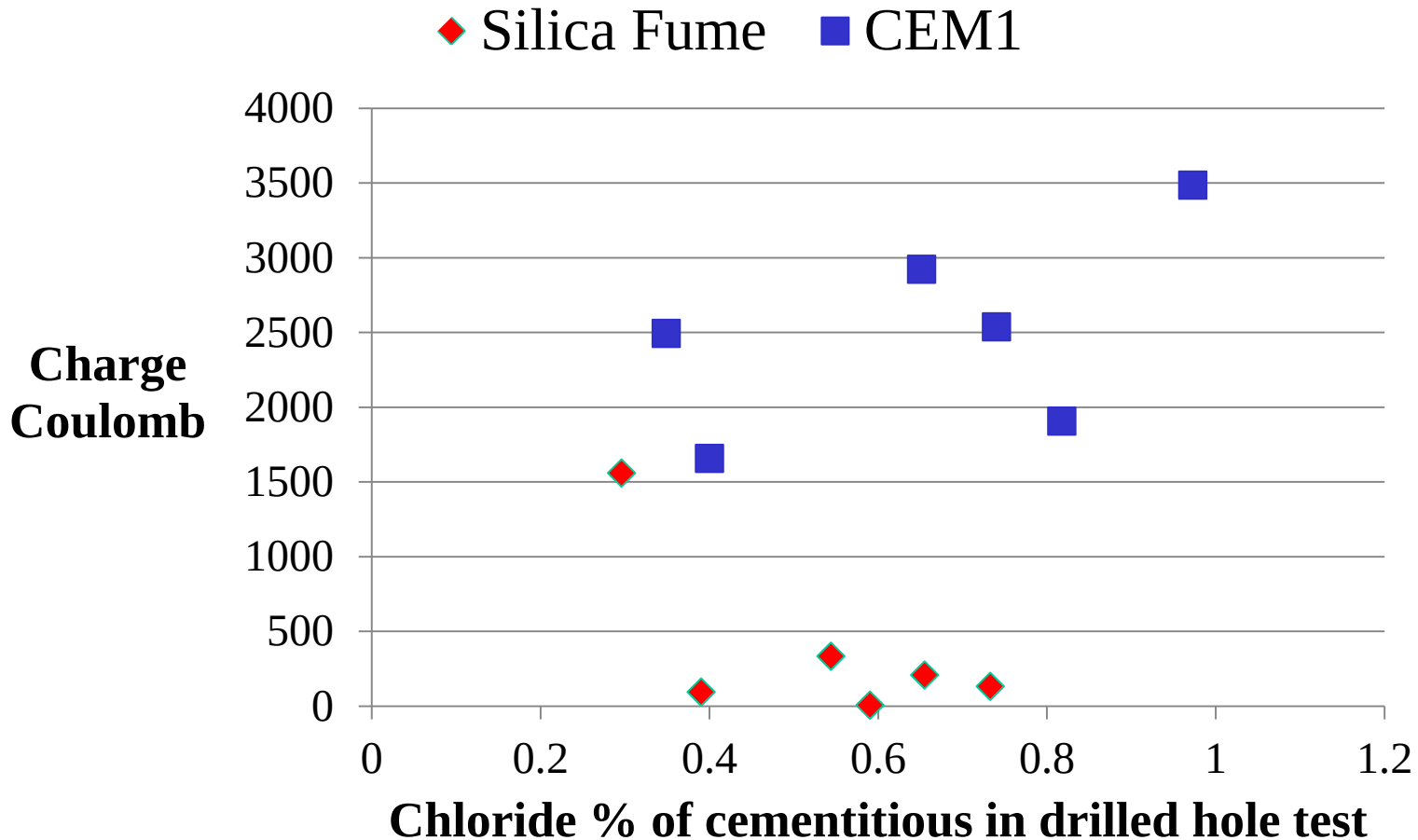
Equation (7) is the integral of Fick's law.

Dint = Intrinsic diffusion coefficient

(3) and (4) coincide – showing that the computer model gives the same results as integrating Fick's law if the ion-ion interactions are switched off.

(5) Is based on experimental data

Comparing simple diffusion with the rapid chloride test.



Selecting an electrical test

- All measurements of diffusion in concrete, with or without applied voltages, are significantly affected by ion-ion interactions.
- For the comparison of mixes with different cementitious materials in them a simple diffusion test should be used unless computer modelling is used to correct the results of electrical tests.
- The electrical tests are suitable for quality control purposes.
- For modelling the life of structures a diffusion coefficient which includes some “adjustment” for ion-ion interactions (such as that obtained by applying Fick’s law to a simple diffusion test) should be used.

Transport Properties of Concrete: Measurement and applications

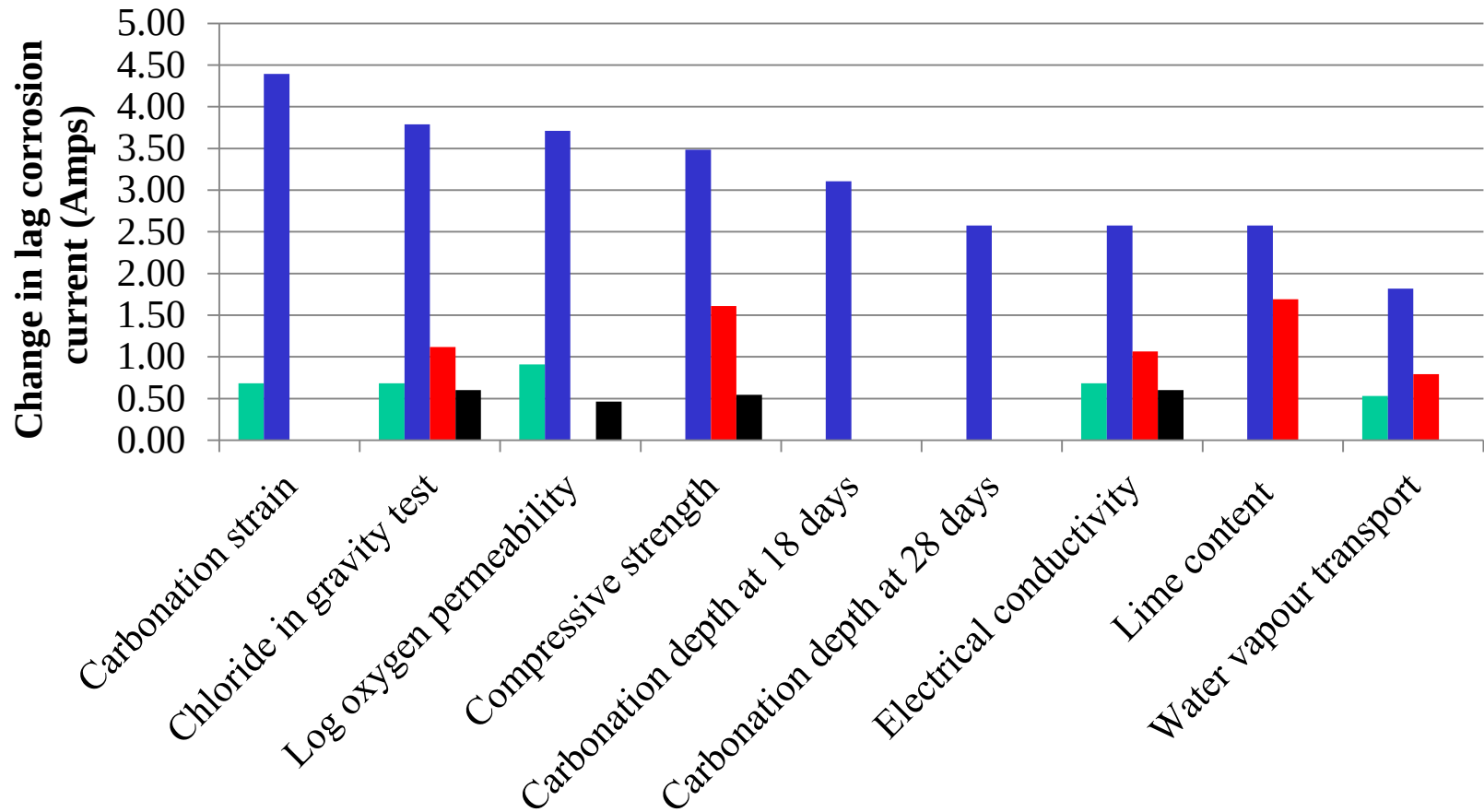
- The transport processes
- Processes which promote or inhibit transport
- Surface permeability tests
- Electrical tests
- Application of the results
 - Durability
 - Waste containment

Factors Affecting Durability

Factors which can be controlled		Properties of the matrix		Transport Processes		Deterioration Processes
		Hydrate Structure		Pressure driven flow		Freeze-Thaw
Water to cement ratio		Pore interconnection (formation factor)		Diffusion		Sulphate Attack
Curing conditions		Porosity (total pore volume)		Electromigration		Alkali-silica reaction
Environmental conditions		Pore fluid content		Thermal Gradient		Reinforcement Corrosion
Degree of compaction		Pore fluid chemistry		Osmosis		Salt Crystallisation
Cement Type		Matrix chemistry		Capillary suction		
				Adsorption		

Effect on corrosion current

- Silica fume in curing
- Portland cement in curing
- Silica fume in chloride
- Portland cement in chloride



Novel landfill barrier. Transport with advection and diffusion

Composition

Alkali activated slag or pozzolan concrete containing spent foundry sand and metallurgical slag aggregate

Non-swelling clay or “artificial clay”.

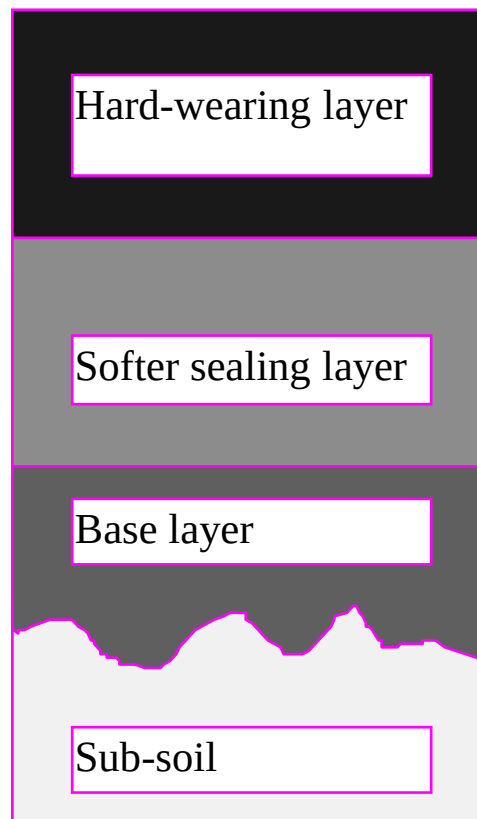
Concrete containing aggregate of larger particles of metallurgical slag and waste and spent foundry sand.

Main Physical Function

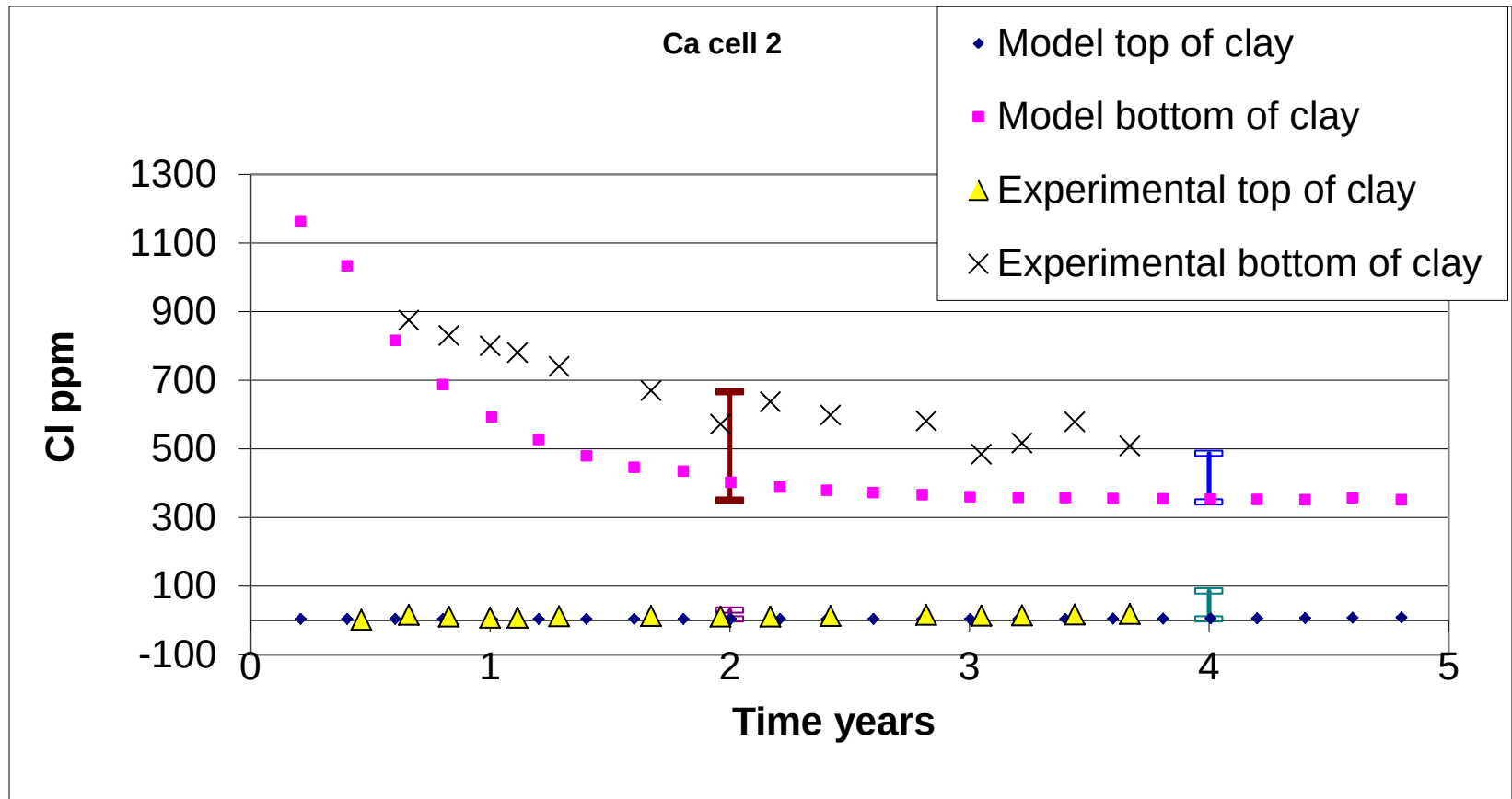
Mechanical support of vehicles during operational phase and initial containment of leachate

Physical containment of leachate and crack sealing.

Chemical conditioning of leachate to promote adsorption and physical containment with low permeability and diffusion coefficient. Base for sealing layer.



Comparing the model with a site trial



Conclusions

- The fundamental transport equations may be applied with either analytical solutions or computer models. The computer models are more versatile.
- Modelling indicates that water tests are better than vacuum tests for surface measurement
- The rapid chloride test should only be used with modelling of ion-ion interactions
- Transport modelling is an effective tool for waste containment modelling

Thank you

www.claisse.info

Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization
**Third International Conference on
Sustainable Construction Materials and Technologies**
Kyoto, Japan, August 18-21, 2013. See: www.scmt.org.uk