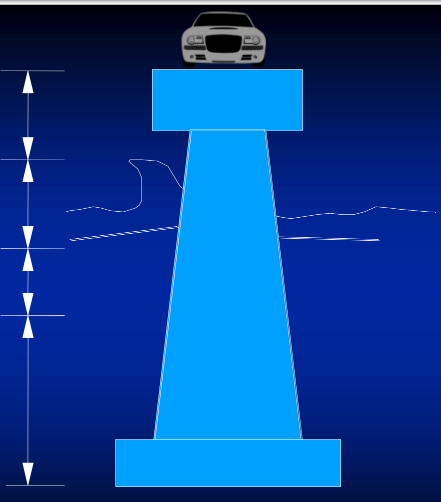
Tests for Measuring Transport Properties

Primary Transport Mechanisms	Exposure Zone
Gas diffusion Water vapour diffusion	Atmospheric
Water vapour diffusion Ionic diffusion	Splash
Water vaour diffusion Water absorption Ionic diffusion	Tidal
Ionic diffusion Water permeability	Submerged



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Permeation/Transport Properties

Adsorption - Physical adherence

Absorption - Capillary suction

Permeability - Pressure gradient

Diffusion - Concentration gradient
- Potential driven

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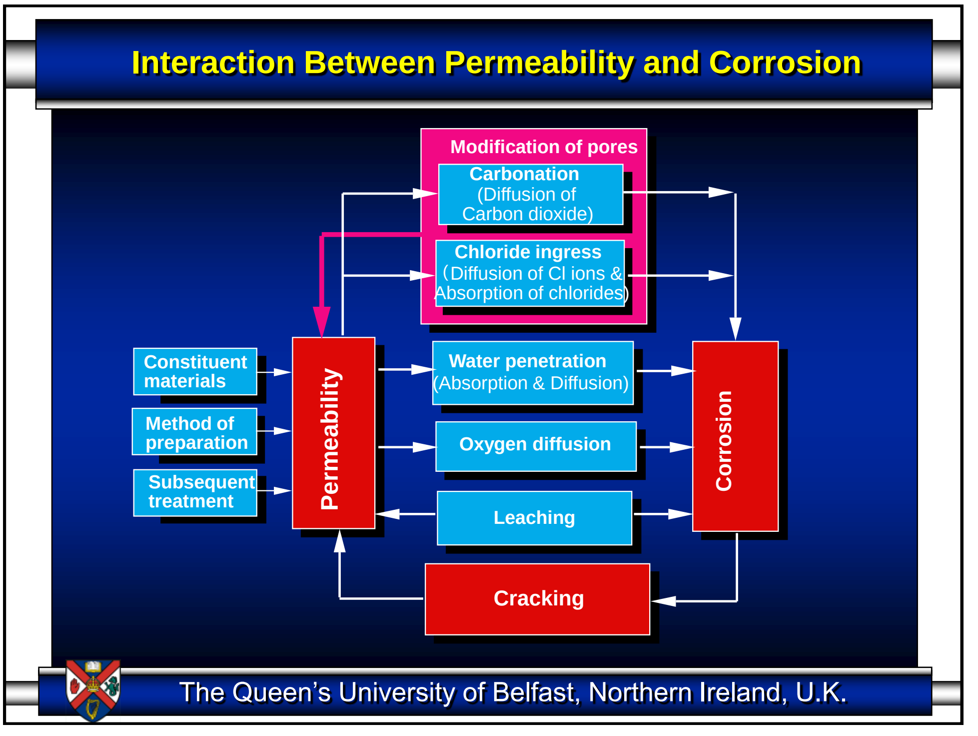
Interaction Between Permeability and Corrosion
Modification of pores
Carbonation (Diffusion of Carbon dioxide)
Chloride ingress (Diffusion of Cl ions & Absorption of chlorides)
Constituent materials
Method of preparation
Subsequent treatment
Permeability
Water penetration (Absorption & Diffusion)
Oxygen diffusion
Leaching
Corrosion
Cracking
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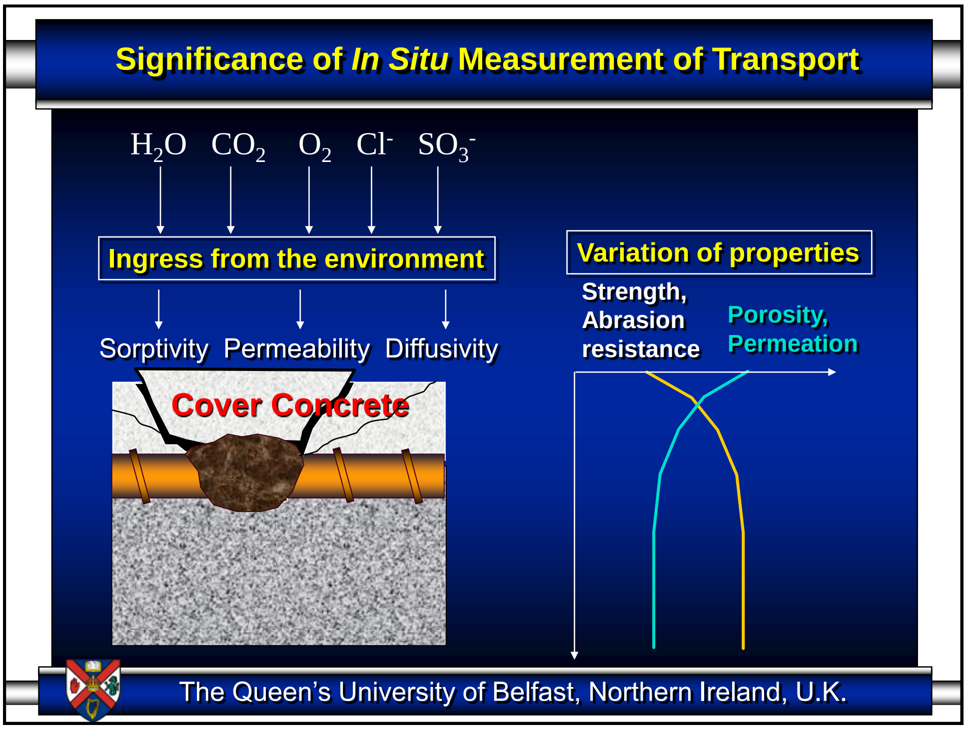
Significance of In Situ Measurement of Transport
H_2O CO_2 O_2 Cl^- SO_3^-
Ingress from the environment
Sorptivity Permeability Diffusivity
Cover Concrete
Variation of properties
Strength, Abrasion resistance
Porosity, Permeation
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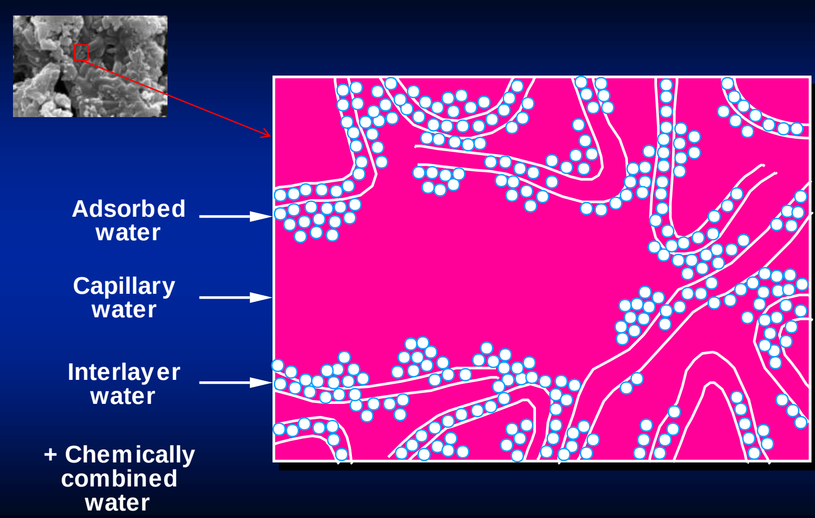
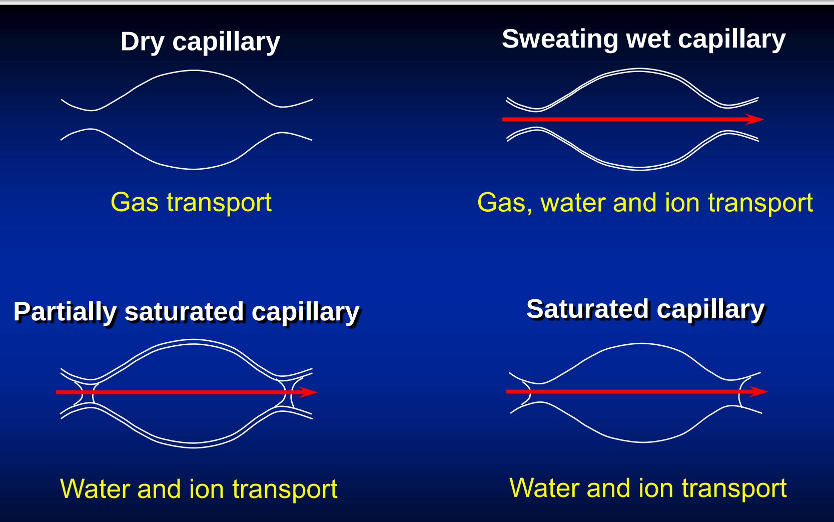
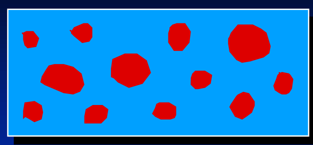
Different Forms of Water in Concrete



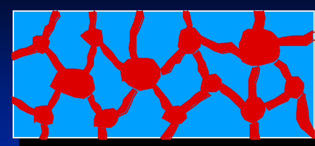
Different Forms of Transport in Concrete Pores



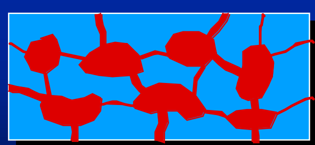
Difference Between Porosity and Permeability



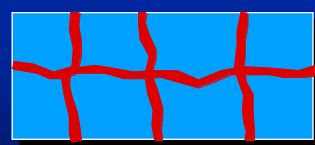
High porosity, No Permeability



High porosity, High Permeability



High porosity, Low Permeability



Low porosity, Low Permeability

Test Methods

- Adsorption Tests
  - Laboratory
- Absorption Tests
  - Laboratory
  - Site
    - Surface
    - Intrusive
- Permeability Tests
  - Gas
    - Laboratory
    - Site
  - Water
    - Laboratory
    - Site
- Diffusion Tests
  - Gas
    - Laboratory
  - Ion
    - Laboratory
    - Site

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Test Methods

- Adsorption Tests
  - Laboratory
- Absorption Tests
  - Laboratory
  - Site
    - Surface
    - Intrusive
- Permeability Tests
  - Gas
    - Surface
    - Intrusive
  - Water
    - Surface
    - Intrusive
- Diffusion Tests
  - Gas
    - Laboratory
  - Ion
    - Laboratory
    - Site

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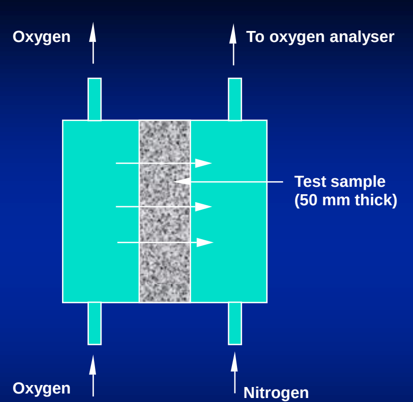
Gas Diffusion Test



Oxygen diffusion test

* Oxygen and nitrogen at equal pressure and temperature passed either side of specimen
* Traces of oxygen detected in nitrogen electrochemically

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Fick's first law

A diffusion coefficient calculated using Fick's first law of diffusion
Approximation dc = Concentration gradient and dx = L thickness; helps to calculate D if J is known

$$J = -D\frac{\partial c}{\partial x}$$

- Rate of diffusion → J
- Diffusion coefficient → D
- dc = concentration gradient
- dx = thickness of sample

$$J = \frac{\partial m}{\partial t}\frac{1}{A}$$

- dm/dt = concentration/mass of substance flowing
- A = exposed area of sample

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Oxygen Diffusion Test

Typical values of oxygen diffusion coefficient at 28 days for concrete conditioned at 55% relative humidity are:

High permeability: > 50 x 10^{-8} m^2/s
Average permeability: 5 x 10^{-8} to 50 x 10^{-8} m^2/s
Low permeability : < 5 x 10^{-8} m^2/s

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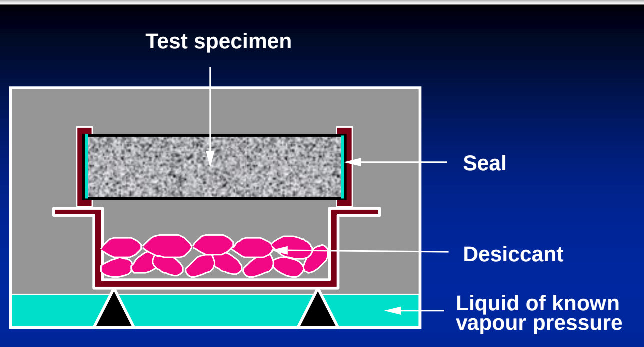
Water Vapour Diffusion Test



Measurement

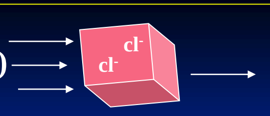
The weight of desiccant at different intervals to determine the weight of water vapour passing through the concrete

Ion Transport Tests

- **In laboratory**
  Diffusion cells
  Chloride ponding tests
  Accelerated chloride migration tests
  (ASTM C1202 & AASHTO T277-83)
- **On site**
  Chloride permeability test
  Use of chloride concentration profiles
  Permit Ion Migration Test

Ionic transport through concrete

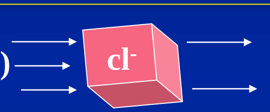
chlorides (cl^-)



Non steady state flow

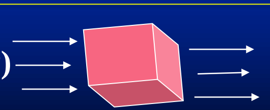
Retention of chloride ions - Binding

chlorides (cl^-)



Non steady state flow

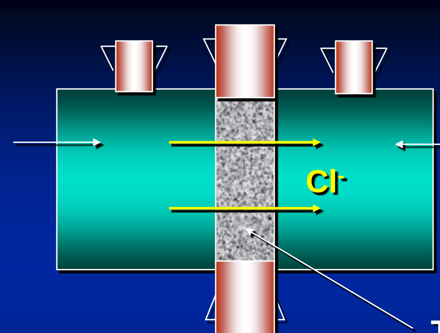
chlorides (cl^-)



Steady state flow

Diffusion cells

1 M NaCl + Saturated $Ca(OH)_2$

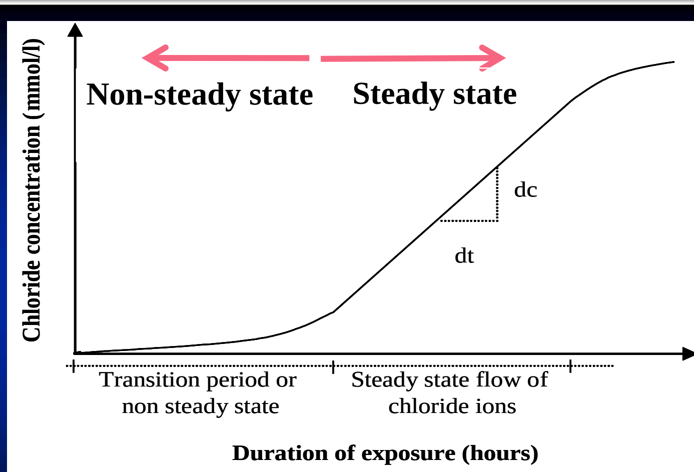


Saturated $Ca(OH)_2$

Test specimen

Diffusion occurs under a concentration gradient, governed by Fick's laws of diffusion

Movement of chloride through sample



$$J = -D\,\frac{dc}{dx}$$

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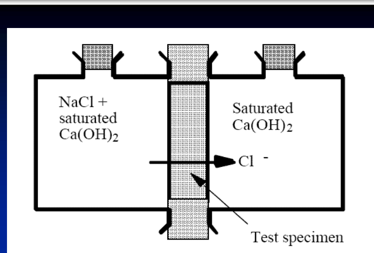
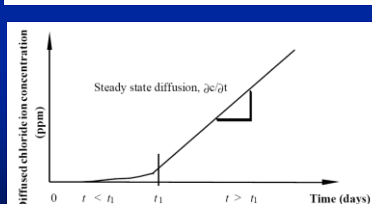
Review: Steady State Diffusion Tests





- Steady state diffusion test
- Cl^- concentration in sink solution is monitored
- Fick's first law
- D_e or D_s is obtained

Limitation

- Long test duration (up to 1 year)
- Cores have to be extracted from structure

Normal Diffusion Test

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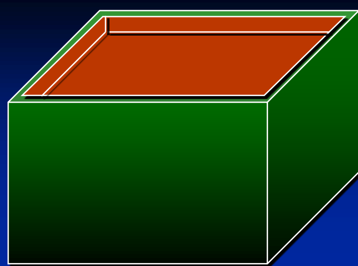
Non-steady test - Chloride ponding test



Non-steady state of diffusion occurs, governed by Fick's second law of diffusion

$$\frac{\delta c}{\delta t} = D \frac{\delta^2 c}{\delta x^2}$$

Solution is in the form

$$C(x,t) = C_0\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

where

C_0 is the surface concentration of chloride ions

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Method of measurement

Profile Grinder or using concrete drill

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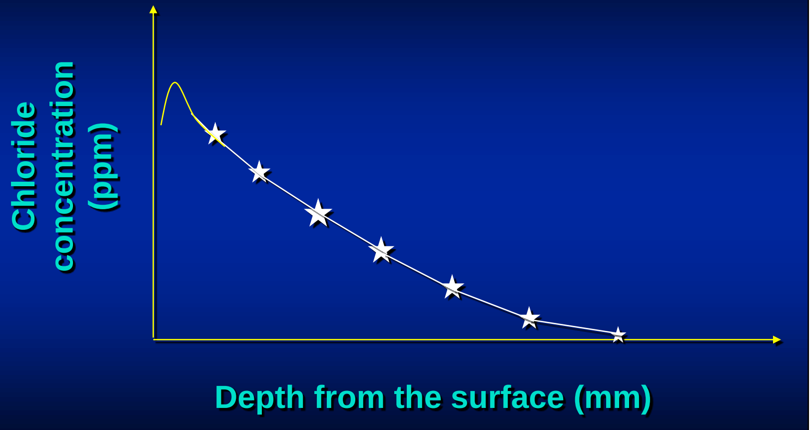
Typical chloride profile in non-steady chloride penetration



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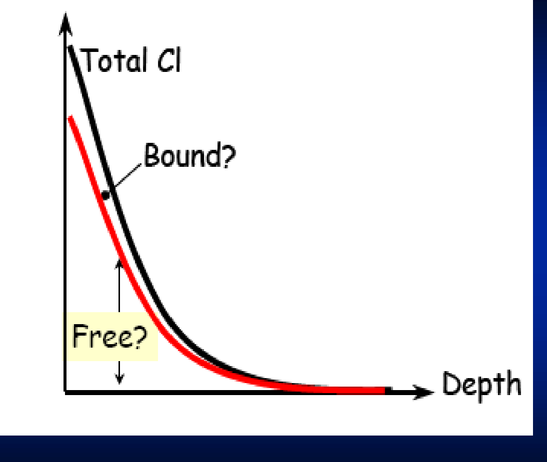
Drawbacks of measurement



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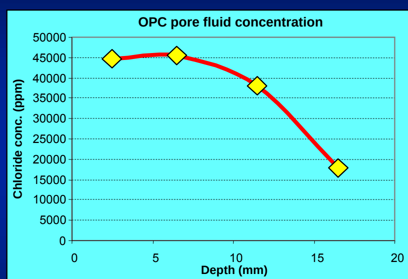
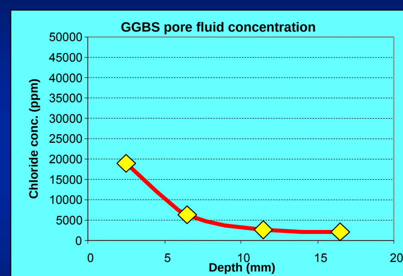
Limitations of Using Chloride Profiles

Free chloride concentration

OPC



GGBS



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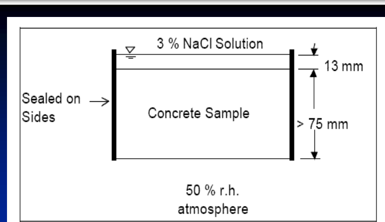
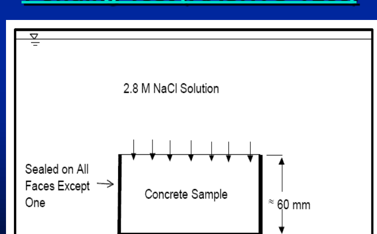
Review: Non-Steady State Diffusion Tests



Ponding Test (AASHTO T259)



Immersion Test (Nordtest NT Build 443)

- Non-steady state diffusion test
- Cl^- profile/depth is determined
- Fick's second law
- D_a or D_{ns} is obtained

Limitation

- Change with time

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Alternative methods of measurements

- A simple equation for mass transfer (Nernst-Planck)

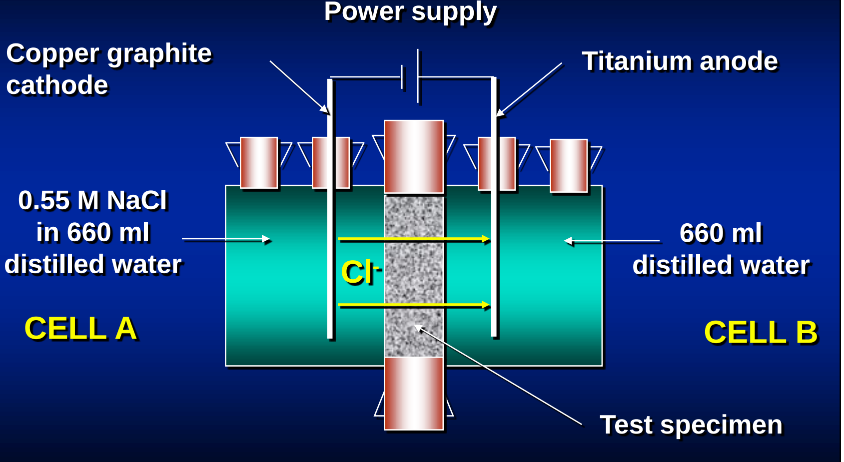
$$\frac{\partial C}{\partial t} = \frac{D_{nssd}\partial^2 C}{\partial x^2} + \frac{D_{mig} zF}{kT}\frac{V}{l}\frac{\partial C}{\partial x} + q_1 C + q_0$$

diffusion · migration · binding

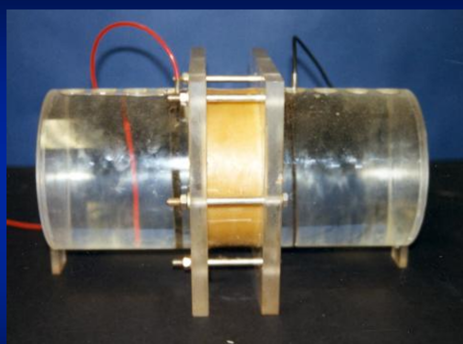
- In words

Rate of change of ions (in the small volume)	=	Ions leaving the volume due to diffusion	+	Ions leaving the volume due to migration	+	Bounded ions leaving the volume

The Chloride Migration Test



The Chloride Migration Test



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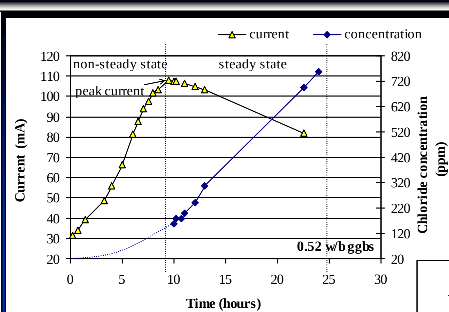
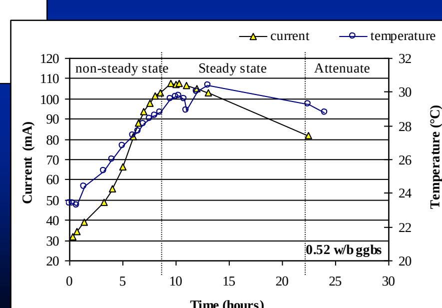
What happens in a migration test?



Chloride concentration
Current – charge passed
Temperature



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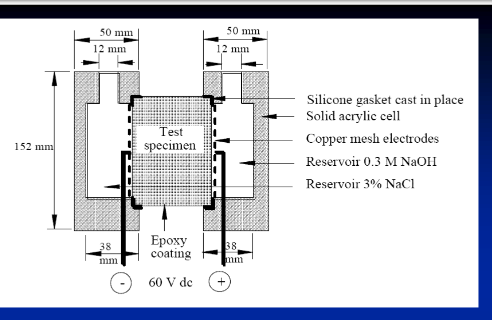
Accelerated Tests – Charge passed



Charge Passed (coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

Limitations

- Total charge is measured, not that only corresponding to the Cl^- flow
- Does not distinguish between chloride flow plus reaction and simple flow
- High voltage induces heat which in turn changes the flow speed
- Can not apply to the concrete containing supplementary materials
- Cores have to be extracted from structure

Rapid Chloride Permeability Test (AASHTO T277 & ASTM C1202)

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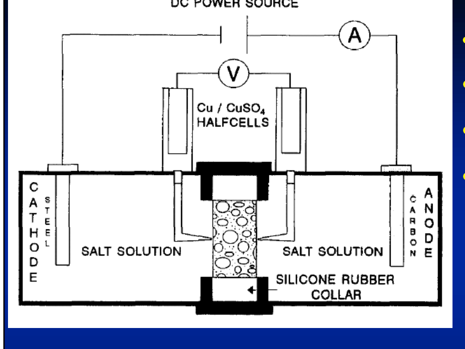
Accelerated Tests – current in direct



- Non-steady state test
- Current is monitored
- Nernst-Einstein equation
- D_{ns} or D_{mig} is obtained

Limitations

- Pore solution extraction or pre-saturation with salt solution
- Vacuum saturation
- High quality concrete can not be fully saturated
- Cores have to be extracted from structure

Conductivity Test

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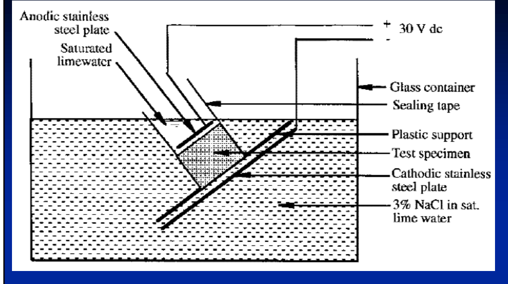
Accelerated Tests – chloride flow



- Non-steady state test
- Cl^- depth is monitored
- Nernst-Einstein equation
- D_{ns} or D_{mig} is obtained

Limitation

- Cores have to be extracted from structure

CTH Test or NT Build 490

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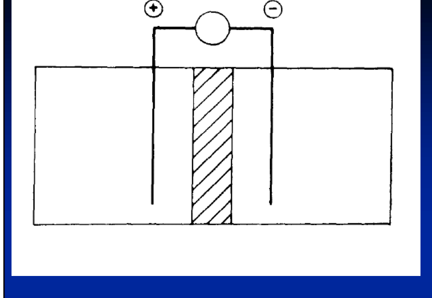
Accelerated Tests – chloride flow



- Steady state test
- Cl^- concentration in anolyte is monitored
- Nernst-plank equation
- D_s or D_{mig} is obtained

Limitations

- Cores have to be extracted from structure
- Chloride concentration has to be measured periodically or liquid samples have to be taken during both non-steady state stage and steady state stage

Steady State Migration Test (NordTest Build 355)

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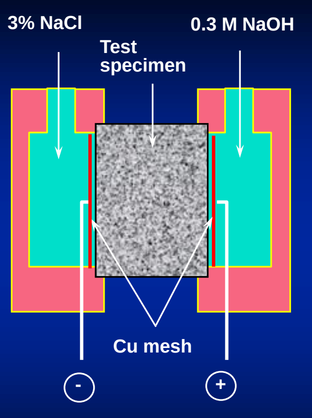
Rapid Chloride Permeability Test – current/charge



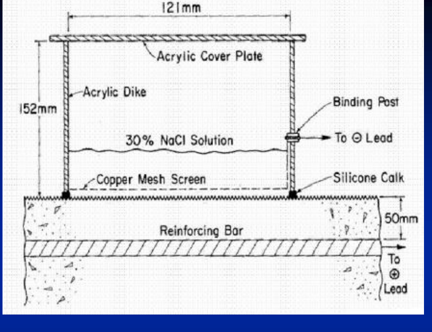
Measurement

Amount of electric current passed through the concrete over a duration of 6 hours under an applied voltage of 60 V dc.

The total charge passed in coulombs obtained

ASTM C1202 and AASHTO-T277

Review: *In Situ* Accelerated Tests

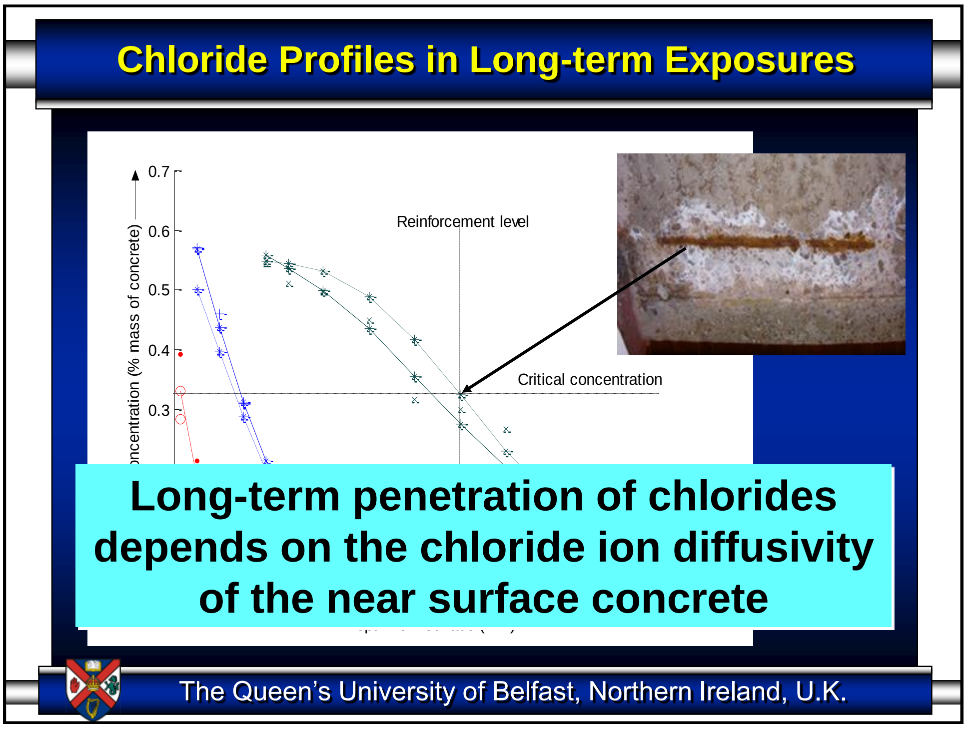


- Non-steady state test
- Current is monitored

- **Not reliable!**
- **Not theoretically sound!**
- **Development discontinued!**

Limitation

- Total charge is measured, not that only corresponding to the Cl^- flow
- High voltage induces heat which in turn changes the flow speed
- Can not apply to the concrete containing supplementary materials, e.g. silica fume
- The depth of cover concrete varies


Chloride Profiles in Long-term Exposures
0.7
0.6
0.5
0.4
0.3
Reinforcement level
Critical concentration
Long-term penetration of chlorides depends on the chloride ion diffusivity of the near surface concrete
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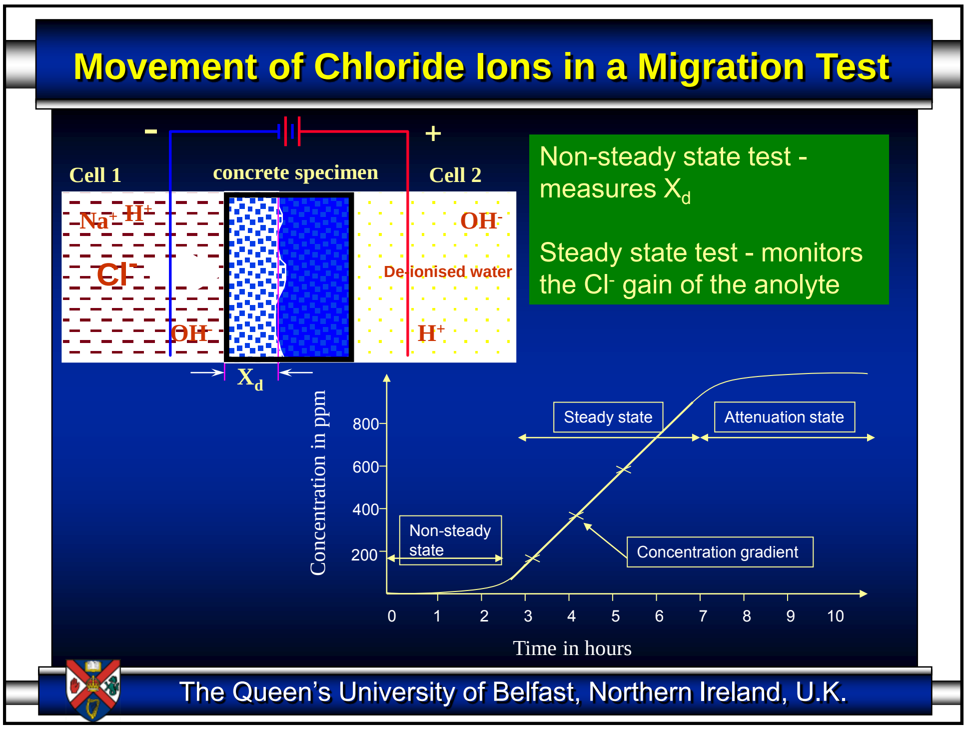
Movement of Chloride Ions in a Migration Test
-
+
Cell 1
concrete specimen
Cell 2
Na+ H+
Cl-
OH-
OH-
Deionised water
H+
Xd
Non-steady state test - measures Xd
Steady state test - monitors the Cl- gain of the anolyte
Concentration in ppm
800
600
400
200
Steady state
Attenuation state
Non-steady state
Concentration gradient
0
1
2
3
4
5
6
7
8
9
10
Time in hours
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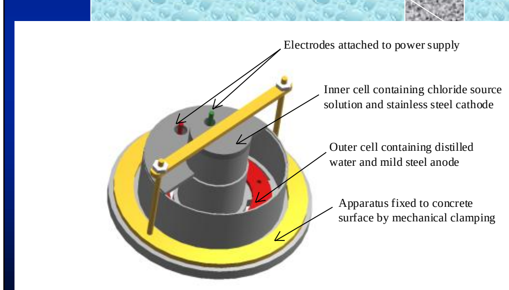
Chloride Ion Penetration Resistance Methods

Summary

Test method	Property obtained	Comment
Diffusion cell	D_e or D_s	Long test duration
Chloride profile/ penetration	D_a or D_{ns}	Changes with time
Migration cells	D_{mig} or D_s	Damage by coring
Conductivity tests	D_{mig} or D_{ns}	Damage by coring Limitations of test set up
Charge measurement	D_{mig} Index	Not specific to Cl^- Influence of binder type

Evolution of the New Ion Migration Test

From NordTest Build 355



Calculation of Migration Coefficient

Based on Nernst-Planck Equation

D_{mig} (m^2/s) = JRTL/zFcE

J = (V/A) (dc/dt); dc/dt is the steady outflow rate,

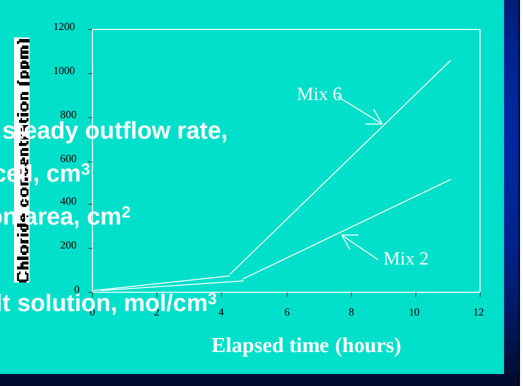
V = the volume of the outer cell, cm^3

A = the average transmission area, cm^2

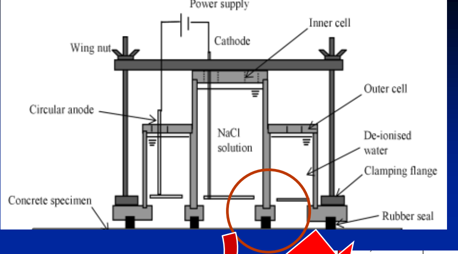
L = average flow length, cm

c = concentration of the salt solution, mol/cm^3

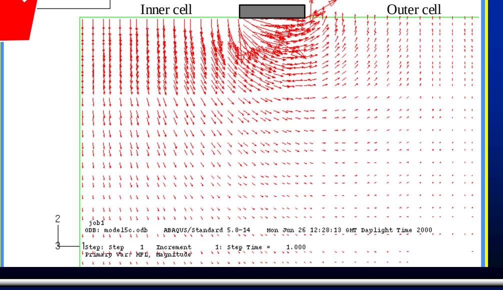
E = applied voltage, v dc



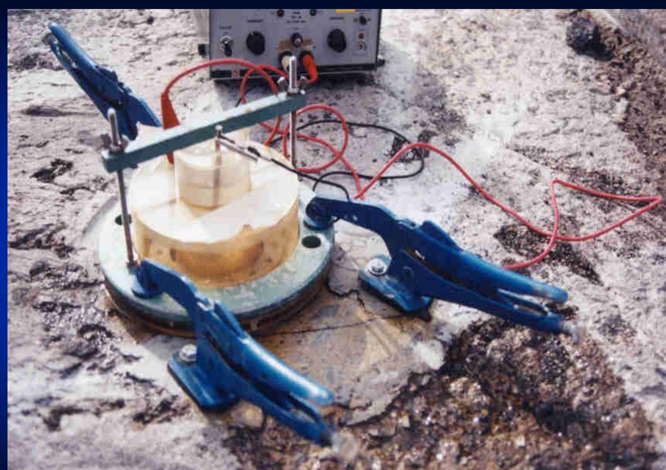
Flow of Chloride Ions in PERMIT



Cl^-



PERMIT Used on a Bridge in Montreal



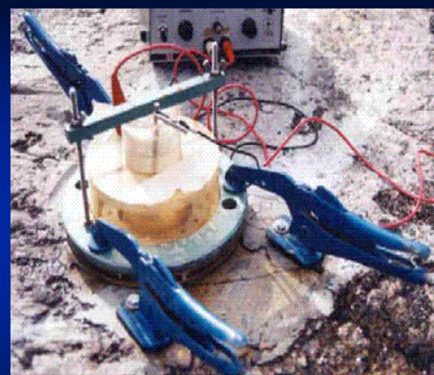
PERMIT Ion Migration Test

Saturate test area

Fix Cells

Description of PERMIT Ion Migration Test

(a) Fixing Using Bolts



(b) Fixing Using Clamps

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PERMIT Ion Migration Test

Connect to power supply and datalogger/PC

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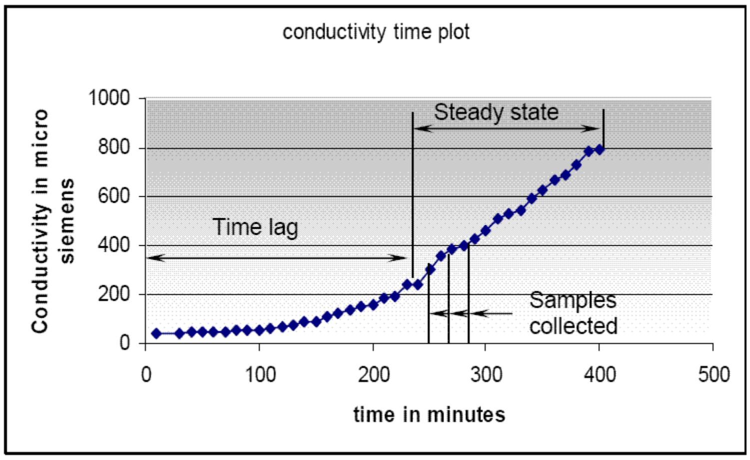
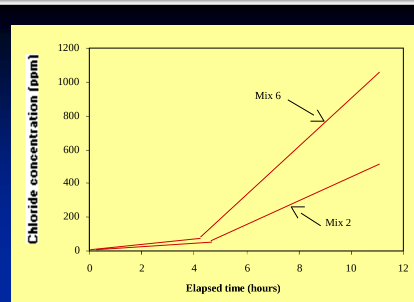
Conductivity of Anolyte for Determining Steady-state



Description of PERMIT Ion Migration Test

D_{mig} = JRTL/zFcE

(based on Nernst-Planck Equation)



J = (V/A) (dc/dt); dc/dt is the steady outflow rate,
V = the volume of the outer cell, cm^3
A = the average transmission area, cm^2
L = average flow length (= 2.72cm)
c = concentration of the salt solution, mol/cm^3
E = applied voltage, v dc

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Assumptions Made in PERMIT Migration Test

- Concrete is saturated
- Chloride flux is ONLY due to electric field
- No buffer effect on migrating ions
- Medium stays neutral during the test

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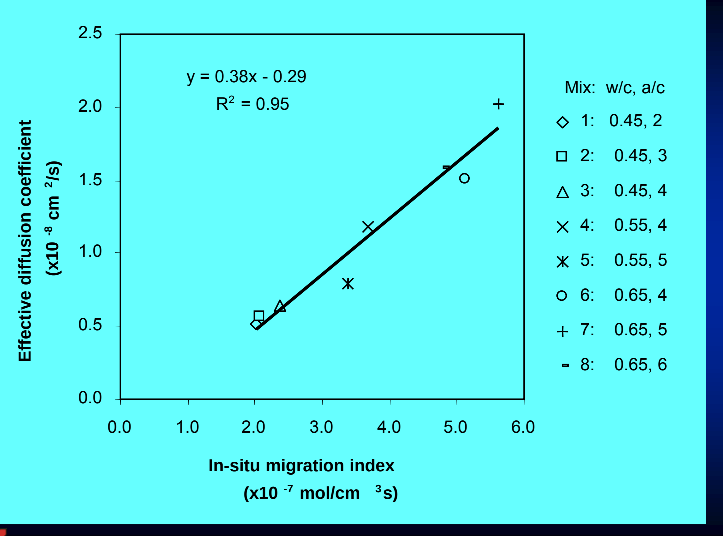
Validation against D_e (1-D) for OPC Mixes



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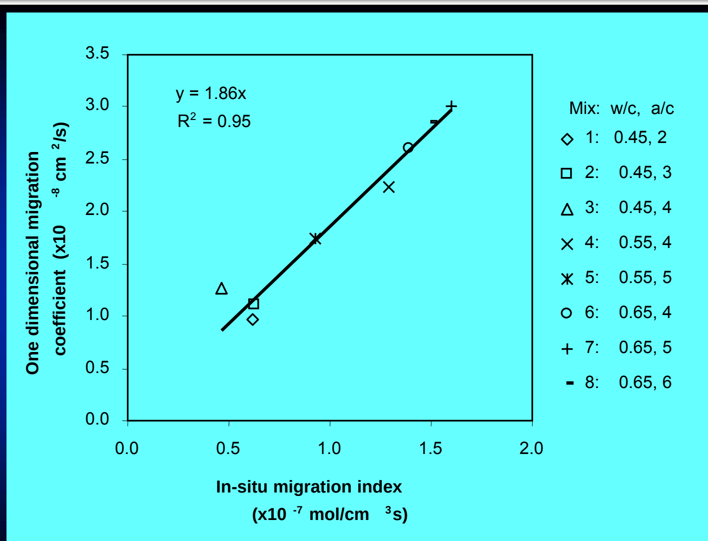
Validation against D_{mig} (1-D) for OPC Mixes



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Specifying concrete based on $D_{in\ situ}$

Deemed to satisfy $D_{in\ situ}$ values for exposure to chloride environments –XS3 - UK

	Common Structures	Monumental Structures	
Service Life	50 years	100 years	100 years
Minimum Cover (mm)	50	50	75
$D_{in\ situ}$ ($10^{-12}m^2/s$) at 6 months	≤0.30	≤0.15	≤0.35

Note: Modelled values based on an assumed critical chloride threshold of 0.1% by mass of concrete. $D_{in\ situ}$ measured in controll samples kept in laboratory conditions at an age of 6months.

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PERMIT Ion Migration Test

Surface Discolouration Due to the Test
(when mild steel anodes are used)

Test Methods

- Adsorption Tests
  - Laboratory
- Absorption Tests
  - Laboratory
  - Site
    - Surface
    - Intrusive
- Permeability Tests
  - Gas
    - Laboratory
    - Site
  - Water
    - Laboratory
    - Site
- Diffusion Tests
  - Gas
    - Laboratory
  - Ion
    - Laboratory
    - Site

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Absorption Tests

- Tests for water absorption capacity: ← All Surfaces
  determine effective porosity of concrete.
- Sorptivity tests: ← Unidirection
  (Preferred Test)
  determine either the rate of inflow or the depth of water penetration.
- Absorptivity tests: ← Multidirection
  measurement of either the volume of water absorbed in a specific time or the time needed to absorb a specific volume of water.

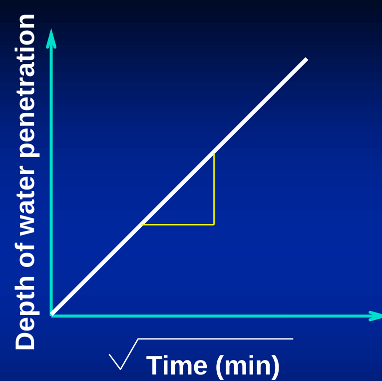
Water Absorption Capacity Test

Specified in ASTM C 642-97, BS 1881: Part 122: 2011 and AS 1012.21-1999

- Typical values based on BS 1881 30 minutes immersion test:

Low absorption concrete:	< 3%
Average absorption concrete:	3-4%
High absorption concrete	>4%

Laboratory Absorption (Sorptivity) Test



$$\frac{\text{Slope}}{\text{area}} = \text{sorptivity}$$

Depth or cumulative volume of water penetrated can be used

In Situ Absorption Tests - Surface Mounted

Karsten's Tube

ISAT

Germann GWT-4000?

Autoclam

Autoclam Permeability System

Different test areas to measure transport on:
- Normal and high performance concretes
- Highly porous concretes
- Surface treated concretes

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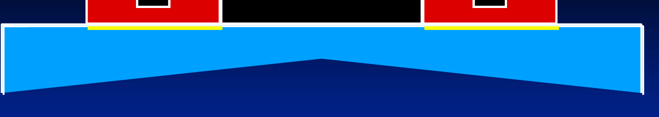
Basis of Operation



Bond steel ring to surface of sample to be teste

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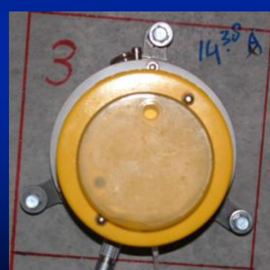
Basis of Operation

Base ring with rubber seal to
eliminate surface damage



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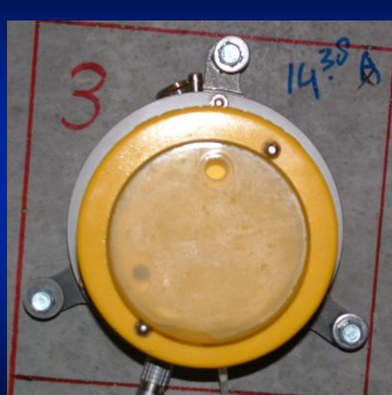
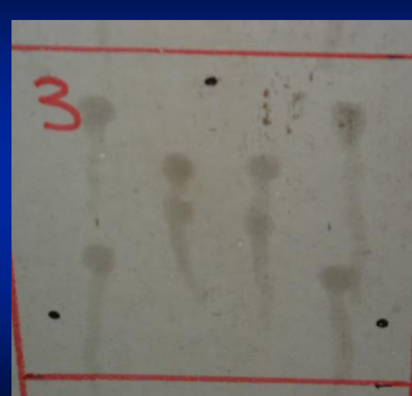
Surface damage due to bolt-on type rings





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Basis of Operation

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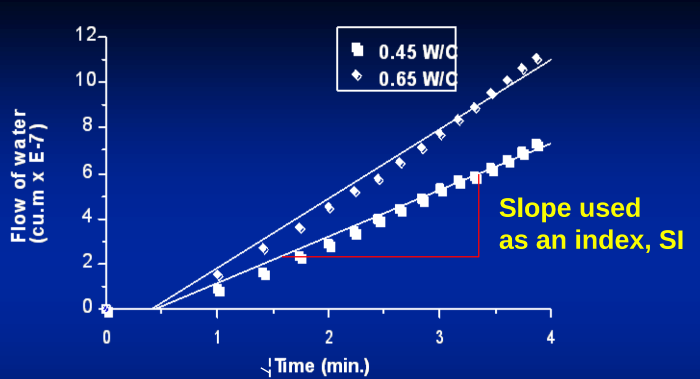
Typical Water Flow Test Data



$$\text{Sorptivity (mm/hour}^{0.5}) = \frac{\text{(SI) x 7746}}{\text{test area}}$$

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Quality Rating based on Autoclam Results

Classification (predicted risk)	AP index	S index	WP index
Low	< 0.1	< 1.3	< 3.7
Medium	> 0.1 ≤ 0.5	> 1.3 ≤ 2.6	> 3.7 ≤ 9.4
High	> 0.5 ≤ 0.9	> 2.6 ≤ 3.4	> 9.4 ≤ 13.8
Extremely high	> 0.9	> 3.4	> 13.8

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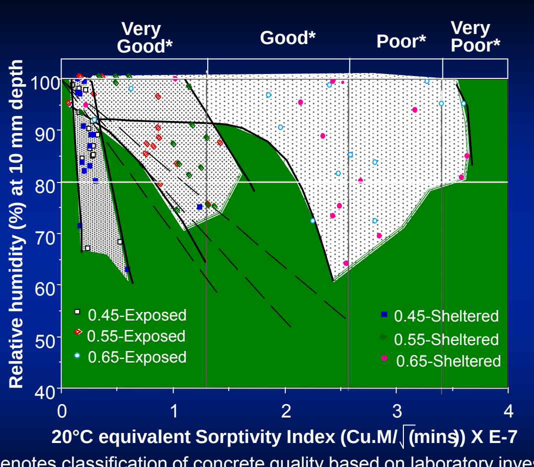
Autoclam Sorptivity vs *In Situ* RH at 10mm Depth



* Denotes classification of concrete quality based on laboratory investigations

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RH Probes to Measure Internal Relative Humidity

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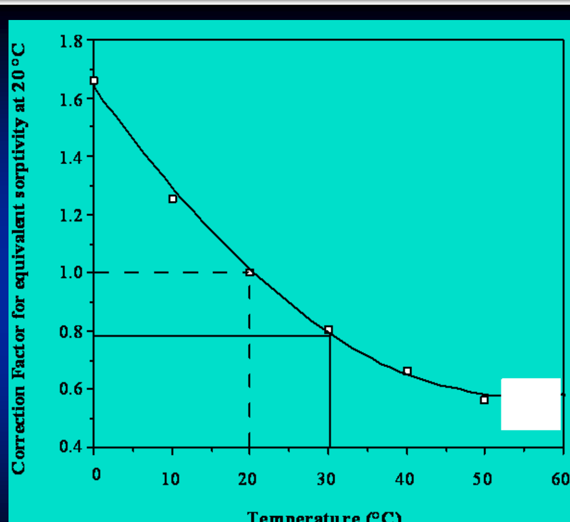
Influence of Temperature on Sorptivity



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  - Gas
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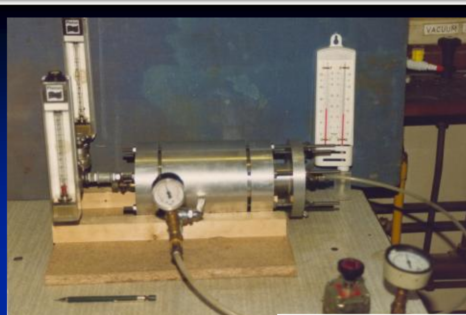
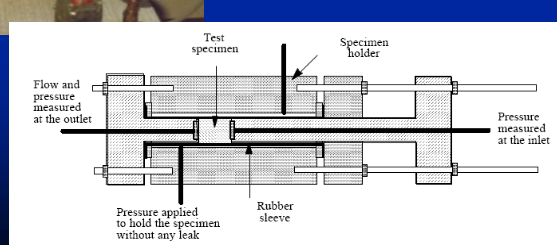
    - Laboratory
    - Site

Gas Permeability Cell





In Situ Gas Permeability Tests – Surface Mounted

Autoclam Permeability System

Torrent Permeability Test

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In Situ Gas Permeability Tests – Intrusive

Poroscope (Figg Air Permeability Test)

Germann GGT-5000

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Autoclam Permeability System

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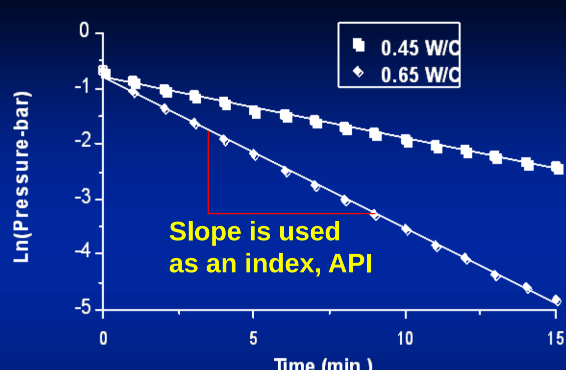
Typical Air Permeability Test Data



$$k_a\,(m^2) = (API)^{0.875} \times 8.395 \times 10^{-16}$$

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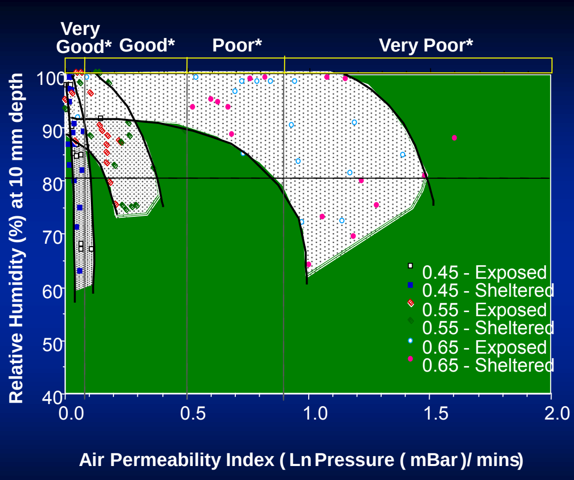
Extremely high	> 0.9	> 3.4	> 13.8

Autoclam Air Permeability vs In-situ RH at 10mm Depth



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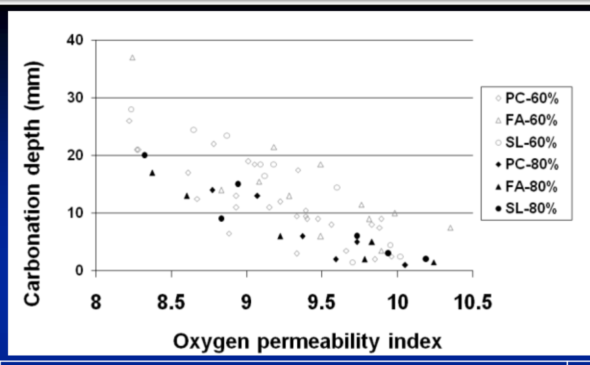
South African Oxygen Permeability Test



Ref:
Private communication
From RILEM PSC Chair

Acceptance Category	Oxygen Permeability (log scale)
Concrete made, cured and tested in the laboratory	> 9,80
Full acceptance of in-situ concrete	> 9,70
Conditional acceptance of in-situ concrete (with remedial measures as approved by the Engineer)	8,75 – 9,70
Rejection	< 8,75

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Test Methods

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    - Surface
    - Intrusive
- **Permeability Tests**
  - Gas
    - Laboratory
    - Site
  - Water
    - Laboratory
    - Site based
- **Diffusion Tests**
  - Gas
    - Laboratory
  - Ion
    - Laboratory
    - Site

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Autoclam Permeability System

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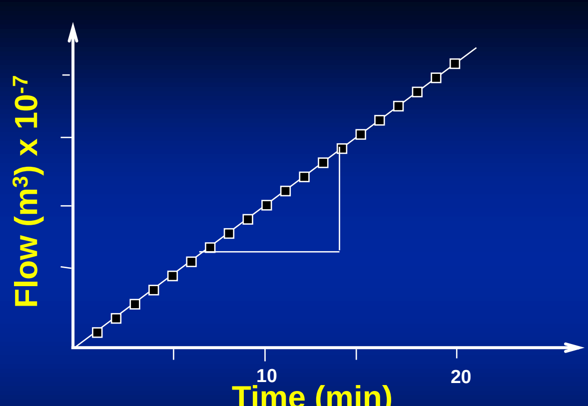
Typical Water Permeability Test Data



k_w (m/s) = q x c where q = rate of steady flow
c = calibration factor

Quality Rating based on Autoclam Results

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Questions

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