**Conference or Workshop Item:**

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# Are alkali activated slag concretes suitable for reinforced concrete structures in chloride environments?

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# Are alkali activated slag concretes suitable for reinforced concrete structures in chloride environments?

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**Structural Faults Repair + European Bridge Conference**
**15th – 17th May 2018, Edinburgh, UK**

# Outline of Presentation

- **Need to assess corrosion resistance of alkali-activated slag cementitious materials**
- **Chloride transport in various AAS concretes**
- **Corrosion of embedded steel in AASC**
- **Suitability of mixes for chloride exposure environments**
- **Conclusions and Recommendations**

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# Advantages of AASC

**AASC can be considered as a low $CO_2$ emission cement ($CO_2$ 20% of PC) and, furthermore, it also:**

- **Uses industry by-products**
- **Consumes less natural resources**
- **Has rapid compressive strength development (more than 68MPa in 24h)**
- **Has high final strength (can achieve 150MPa at 28 days)**
- **Has high resistance against chemical attack**

Building (UR)

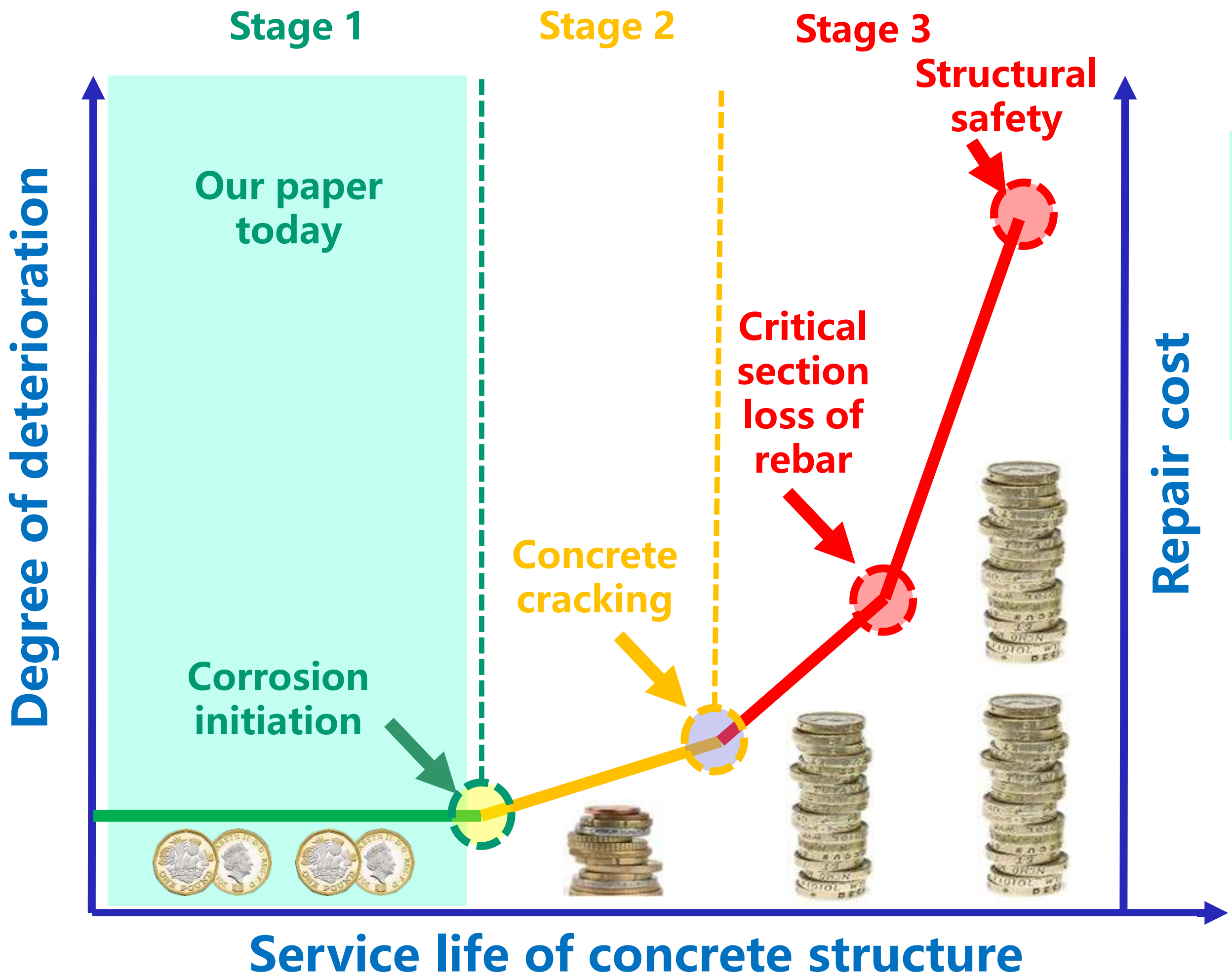
Waste management (UK)

Precast elements (CZ)

Precast walls (AU)

**It is believed that:**
**AAS is a High-Performance binder, AASC is a High-Performance Concrete**

# Context of Investigating Corrosion of Steel in AAS Concrete




## Research focuses at 3 stages:

**State 1:**

① concrete properties (permeation properties)
② transport models
③ corrosion initiation conditions

**State 2:**

① rate of corrosion
② models of corrosion
③ concrete cracking patterns

**State 3:**

① loss of structural capability of elements
② structural safety assessment

# Objectives of Research

i. To study chloride transport in AAS concretes;

ii. To investigate the physical and chemical characteristics of the pore structure and the pore solution of AAS; and

iii. To quantify the time to initiation and rate of corrosion of embedded steel when AAS concretes are exposed to an intermittent chloride ponding regime.

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# Concrete Mix Proportions

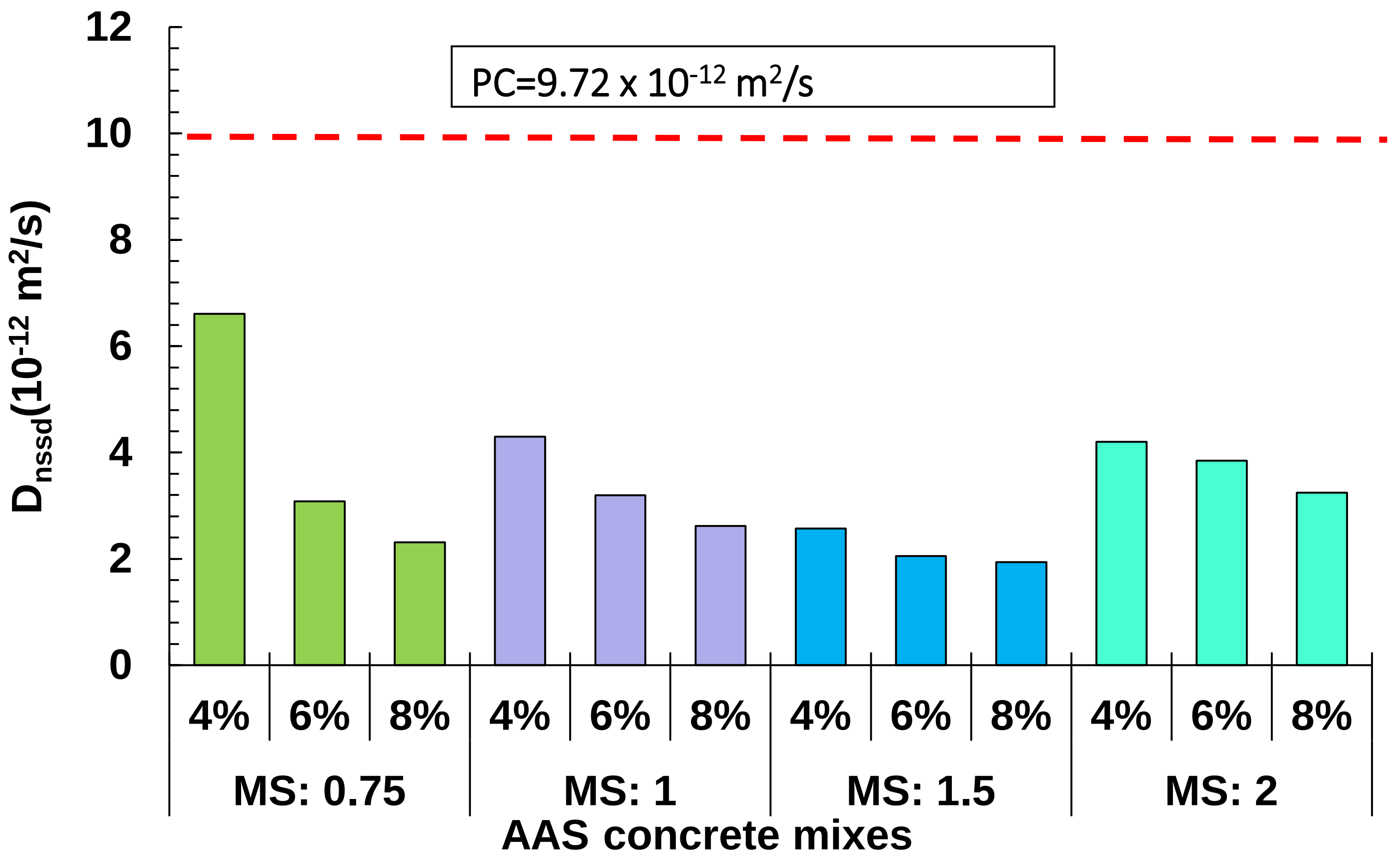
| Mix NO ($Na_2O$-MS) | $Na_2O$ (%) | Ms | Binder (kg/m$^3$) | Sodium silicate (kg/m$^3$) | NaOH (kg/m$^3$) | Retarder (kg/m$^3$) | Sand (kg/m$^3$) | Coarse aggregate (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|
| 4%-0.75 | 4 | 0.75 | 371 | 34.6 | 13.6 | 1.11 | 654 | 1163 |
| 4%-1.00 | | 1.00 | 368 | 45.8 | 11.6 | 1.10 | 655 | 1164 |
| 4%-1.50 | | 1.50 | 362 | 67.7 | 7.8 | 1.08 | 656 | 1167 |
| 4%-2.00 | | 2.00 | 357 | 88.9 | 4.2 | 1.07 | 658 | 1170 |
| 6%-0.75 | 6 | 0.75 | 358 | 19.7 | 19.7 | 1.07 | 654 | 1163 |
| 6%-1.00 | | 1.00 | 354 | 16.8 | 16.8 | 1.08 | 655 | 1165 |
| 6%-1.50 | | 1.50 | 346 | 11.2 | 11.2 | 1.06 | 658 | 1169 |
| 6%-2.00 | | 2.00 | 339 | 5.9 | 5.9 | 1.04 | 660 | 1173 |
| 8%-0.75 | 8 | 0.75 | 346 | 25.4 | 25.4 | 1.02 | 654 | 1163 |
| 8%-1.00 | | 1.00 | 341 | 21.6 | 21.6 | 1.04 | 656 | 1166 |
| 8%-1.50 | | 1.50 | 332 | 14.3 | 14.3 | 1.02 | 658 | 1171 |
| 8%-2.00 | | 2.00 | 322 | 7.5 | 7.5 | 0.97 | 661 | 1175 |
| PC | - | - | 400 | - | - | | 686 | 1220 |

**Note: AASC (w/b = 0.47), Normal Concrete (NC) (w/b = 0.42); Retarder in AASC: Barium based YP-1**

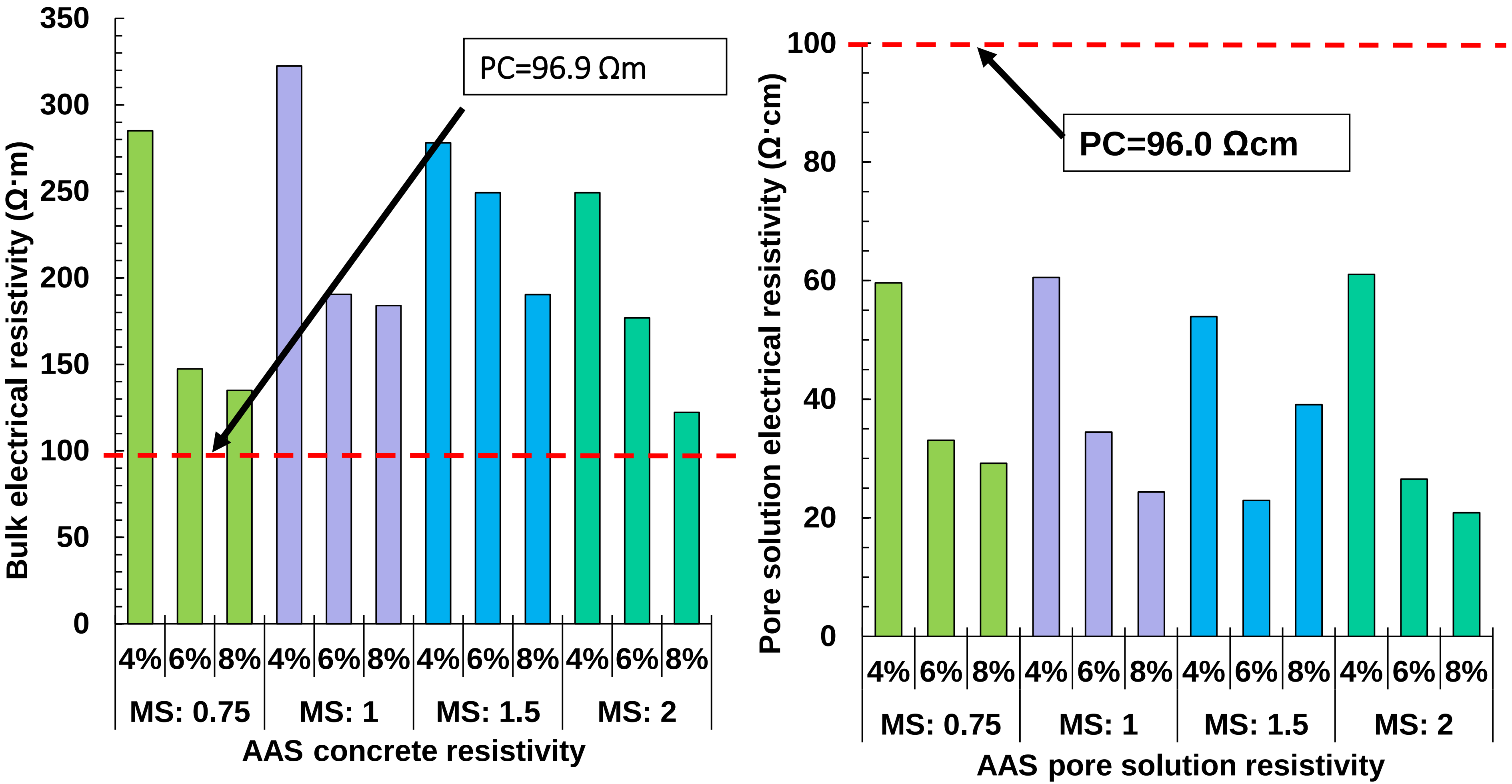
# Properties Measured and Test Methods Used:
# Part 1: Chloride Resistance of AAS Concretes

| Properties measured | Details of Tests |
|---|---|
| Permeation properties | NT BUILD 443 (1995), non-steady state chloride penetration test on 100mm dia. x 50mm thick cores |
| Electrical resistivity | Bulk resistivity of 100mm dia. x 50mm thick cores |
| Pore solution characterisation | Pore fluid expression from 10mm thick concrete slices, followed by the measurement of pH and conductivity of the pore solution |
| Ion analysis | Using inductively coupled plasma-optical emission mass spectrometer (ICP-MS) |
| Slump | BS EN 12350-2 (2009), Part 2: Slump-test |
| Compressive Strength | BS EN 12350-3 (2009), Part 3: Compressive strength of test specimens |

# Chloride Diffusivity: $D_{nssd}$ after 90 Days of Immersion



# Electrical Resistivity of Concretes and the Pore Solutions



# pH, $Na^+$ and $S^{2-}$ of the Pore Solution of AAS Concretes

| Mix ID ($Na_2O$-MS) | pH | $Na^+$ (ppm) | $S^{2-}$ (ppm) |
|---|---|---|---|
| 4%-0.75 | 11.7 | 2154 | 2458 |
| 4%-1.00 | 11.9 | 4740 | 1953 |
| 4%-1.50 | 10.5 | 58.96 | 3786 |
| 4%-2.00 | 9.9 | 121.2 | 4348 |
| 6%-0.75 | 11.9 | 96.26 | 5661 |
| 6%-1.00 | 11.9 | 69.19 | 6210 |
| 6%-1.50 | 11.4 | 42.18 | 6245 |
| 6%-2.00 | 9.9 | 18.20 | 6292 |
| 8%-0.75 | 12.4 | 202.0 | 664.0 |
| 8%-1.00 | 12.2 | 244.0 | 590.0 |
| 8%-1.50 | 10.8 | 185.3 | 618.3 |
| 8%-2.00 | 11.9 | 64.34 | 608.0 |
| PC | 12.5 | 1234 | 329.6 |

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# Properties Measured and Test Methods Used:
# Part 2: Corrosion Resistance of AAS Concretes

| Variable | Parameters investigated |
|---|---|
| Corrosion rate | Rebar mass loss |
| Corrosion distribution | Rebar topography analysis |
| Corrosion rate<br>vs<br>Different parameters | Diffusivity of AAS concrete<br>Electricity of AAS concrete<br>$Na^{+}$ in pore solution<br>$S^{2-}$ in pore solution |

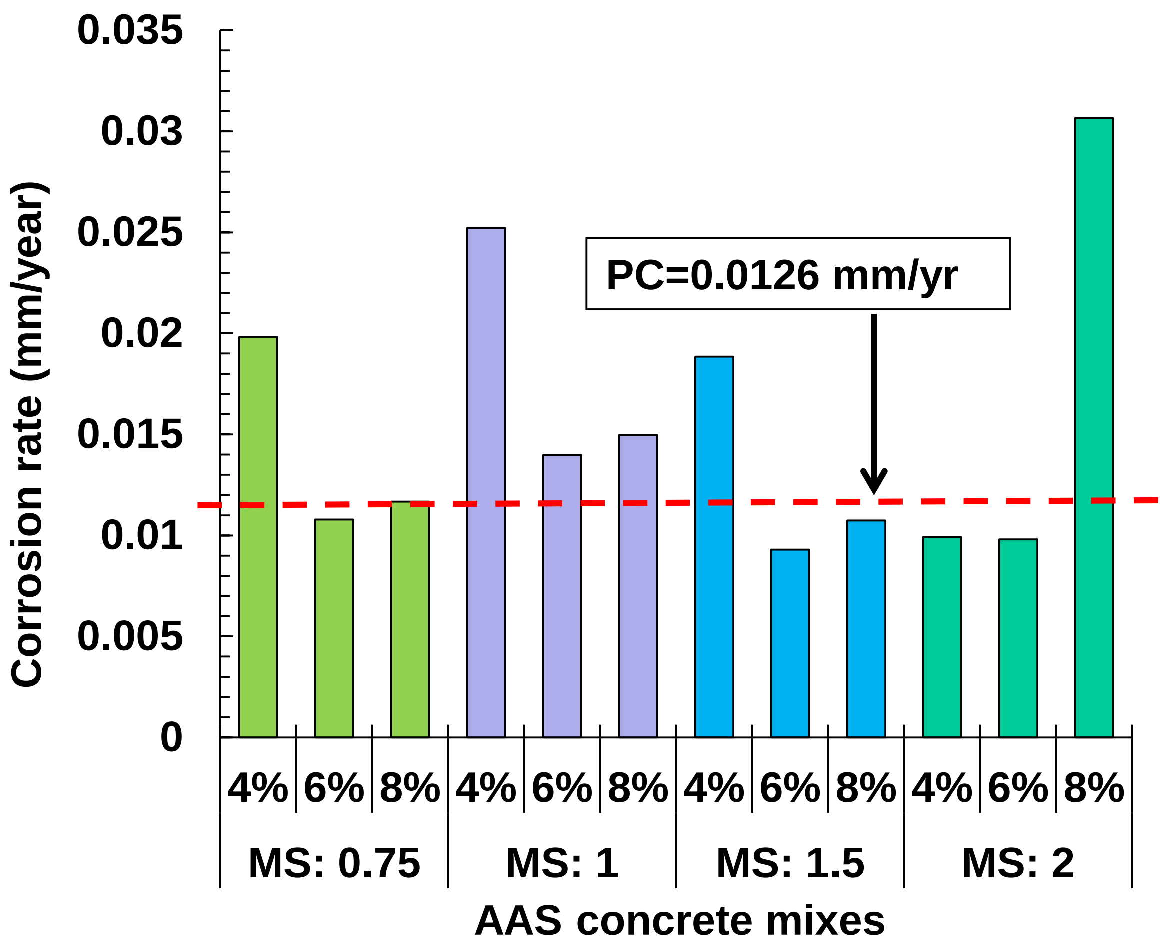
# Test Setup to Study Corrosion Resistance

**Stainless steel electrodes at 15mm, 25mm, 35mm and 45mm depths for electrical resistance measurements**

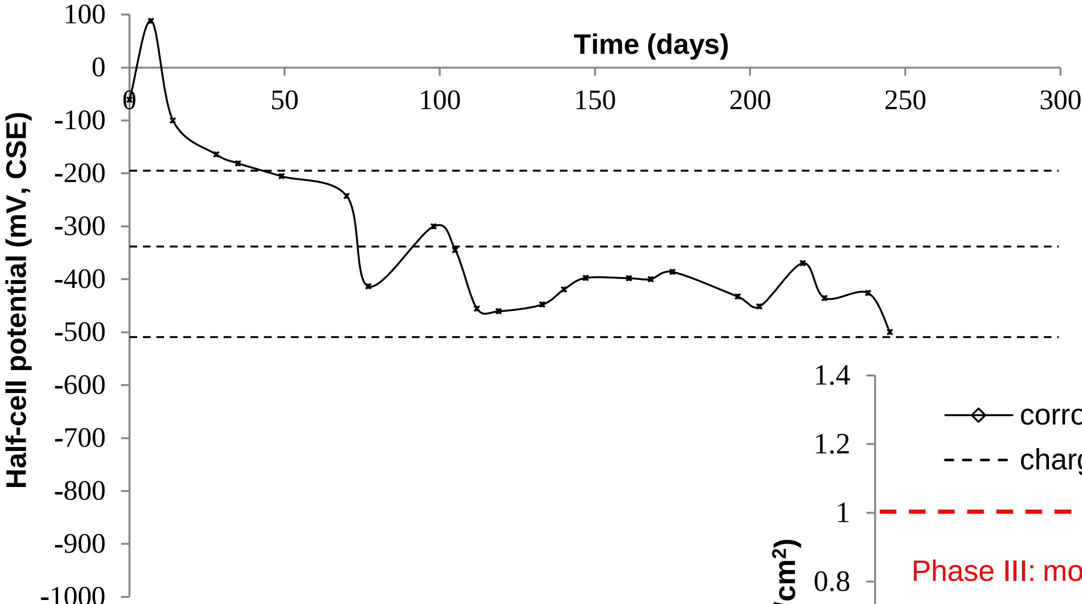
**Top bar to act as anode and the bottom three bars together to act as cathode, connected by a 10Ω resistance**

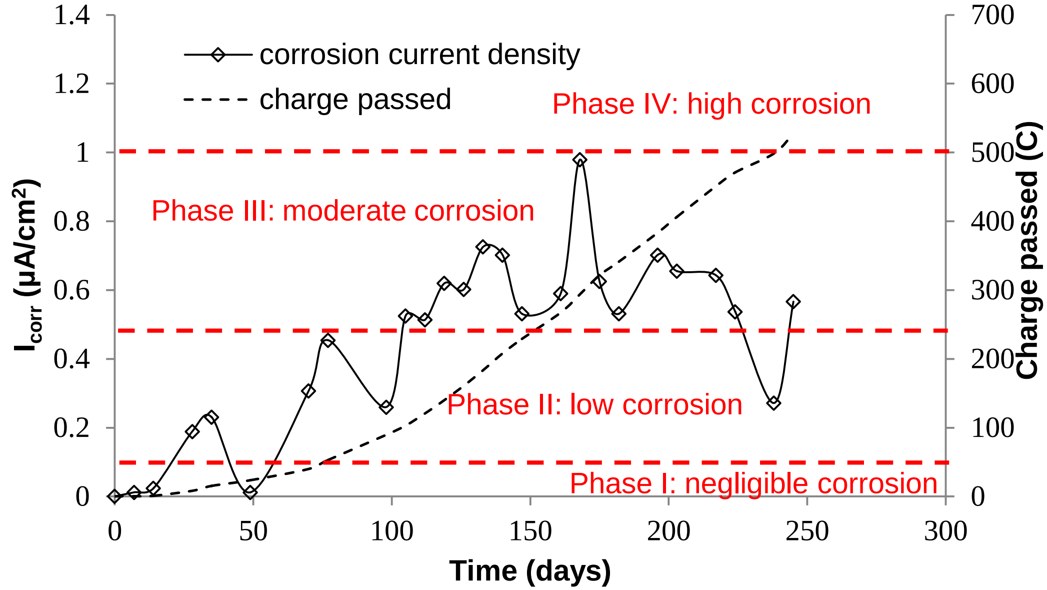
**Weekly cyclic ponding regime with 0.55M chloride solution ponded for 1 day followed by 6 days of drying at $20^0$C**

# Rate of Corrosion in AAS Concretes



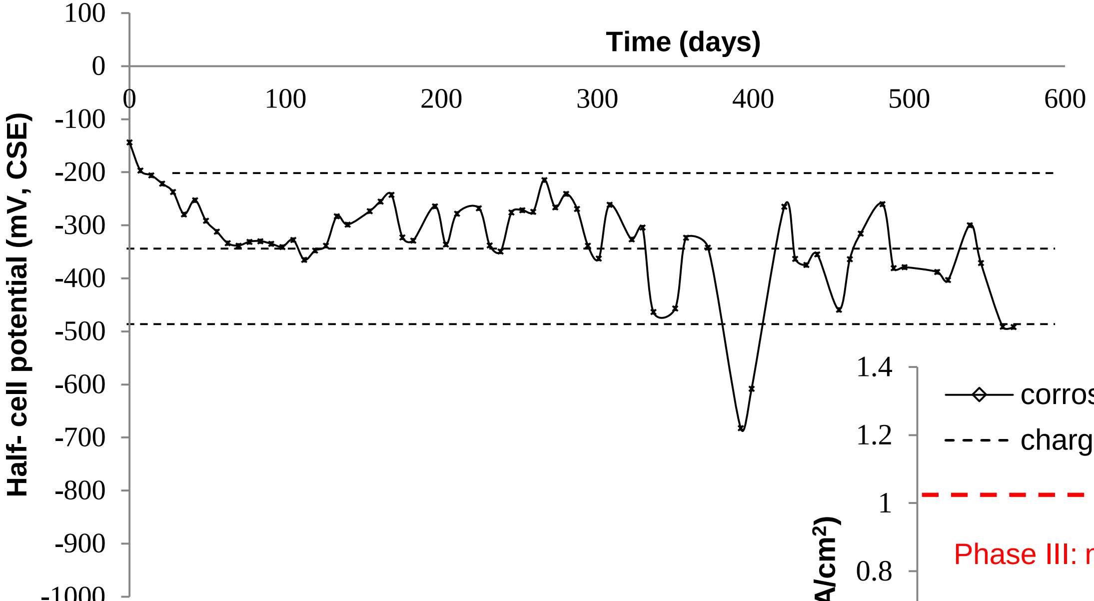

# Half-Cell Potentials and Galvanic Corrosion Data for PC

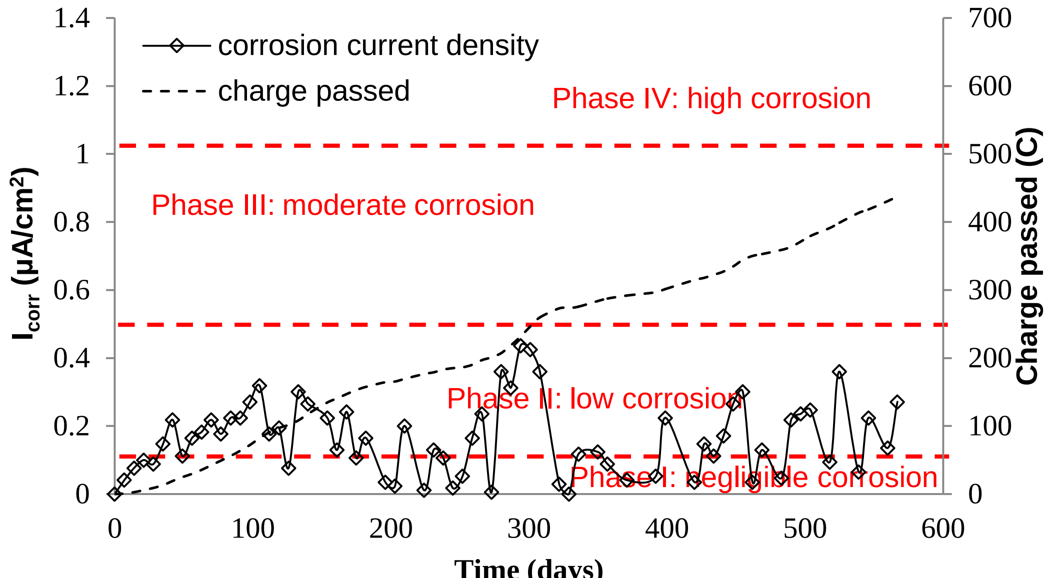



**Both the half-cell potentials and galvanic corrosion measurements could be used to detect the corrosion initiation time in PC concretes.**

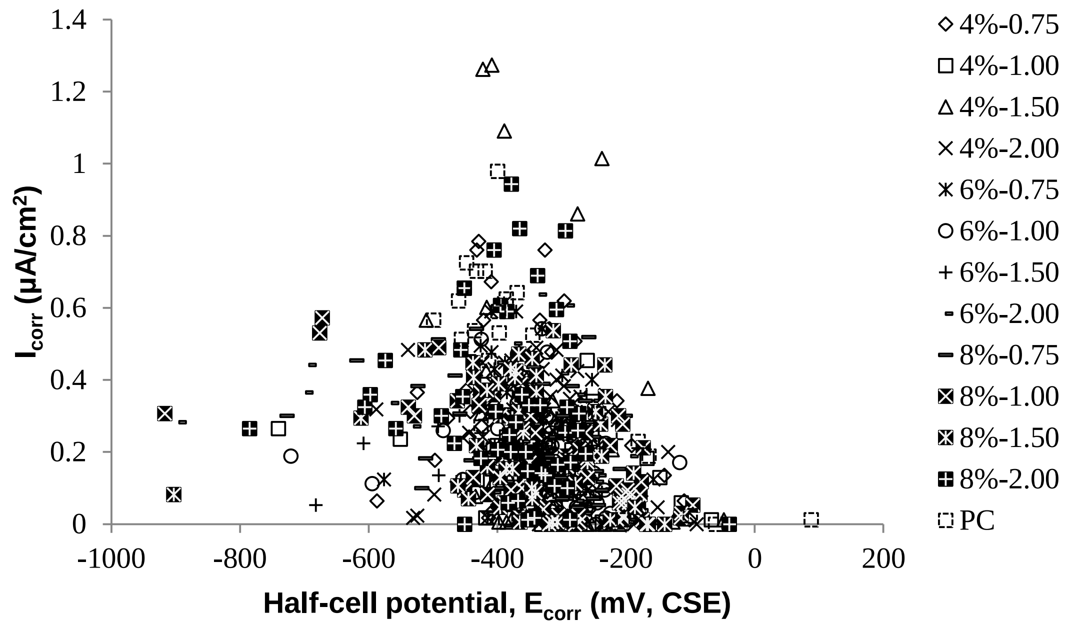
# Half-Cell Potentials and Galvanic Corrosion Data for AASC ($Na_2O$%: 6, Ms: 5.0)



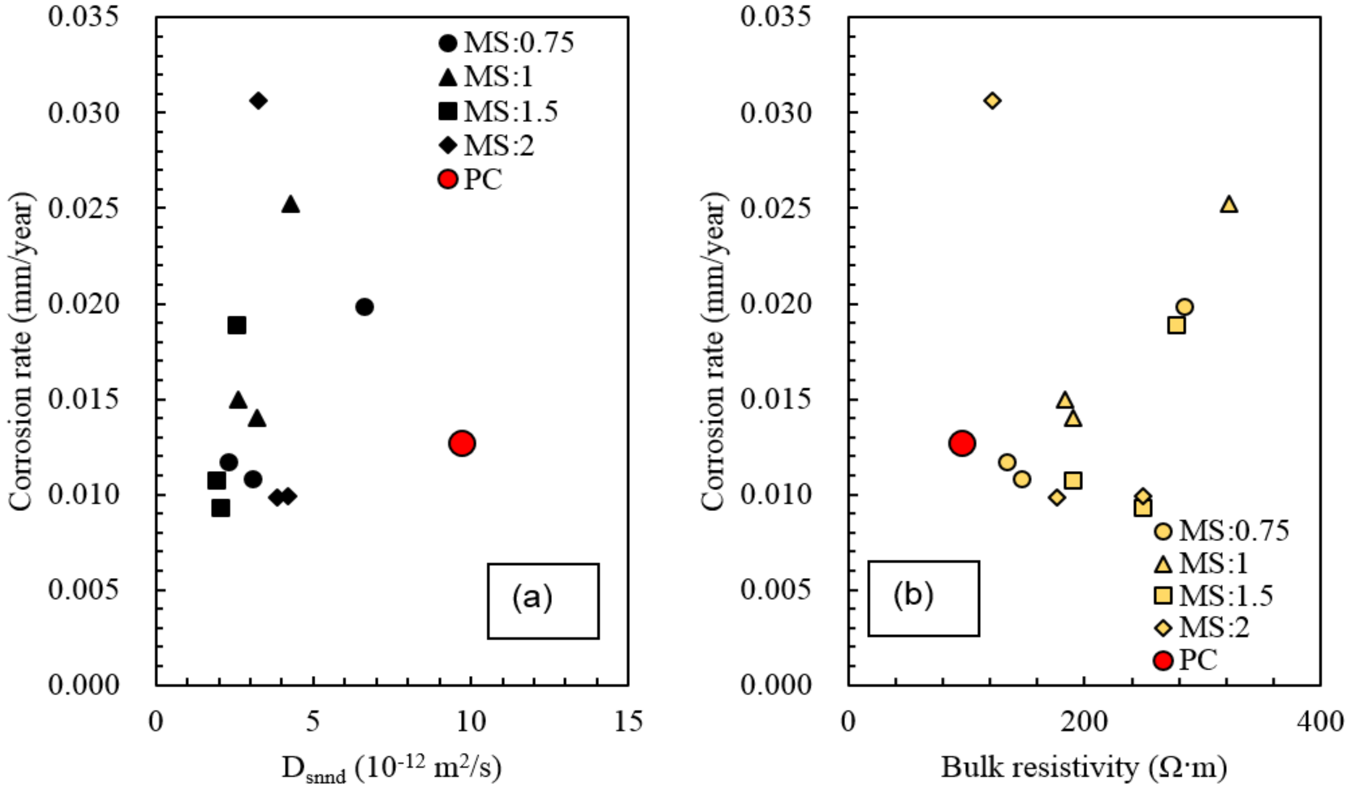




**Half-cell potentials and galvanic corrosion measurements could not be used to detect the corrosion initiation time in AAS concretes.**

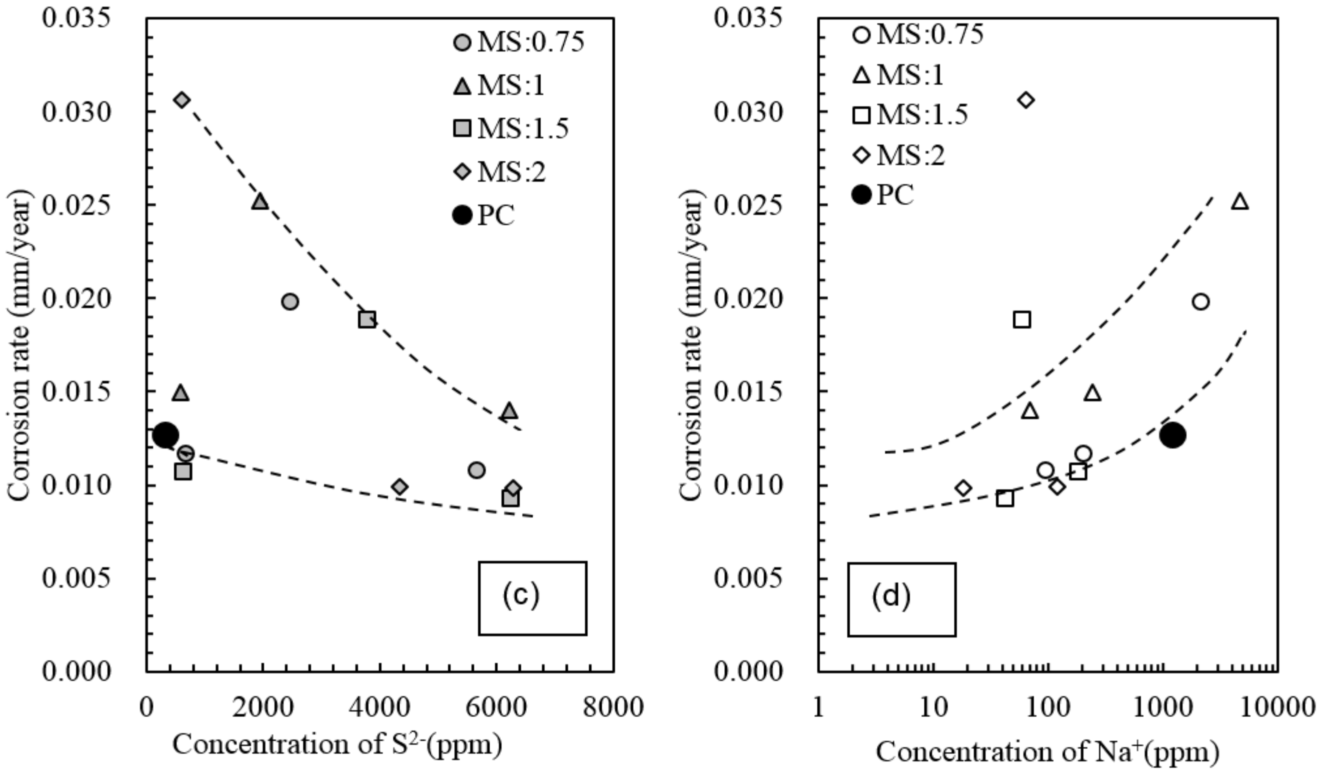
# Relationship Between Half-Cell Potentials and Galvanic Corrosion in AAS Concretes



# Corrosion in AAS Concretes vs Chloride Diffusivity and Bulk Resistivity



# Dependence of Corrosion in AAS Concretes on Sulphide and Sodium Ions in the Pore Solution



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# Exposure Classes from BS EN 206-1

| | | |
|---|---|---|
| **Corrosion induced by chlorides other than from seawater** | | |
| XD1 | Moderate humidity | Concrete surfaces exposed to airborne chlorides |
| XD2 | Wet, rarely dry | Swimming pools, Concrete exposed to industrial water containing chlorides |
| XD3 | Cyclic wet and dry | Parts of bridges exposed to spray containing chlorides Pavements, Car park slabs |
| **Corrosion induced by chlorides from seawater** | | |
| XS1 | Exposed to airborne salt but not in direct contact with seawater | Structures near to or on the coast |
| XS2 | Permanently submerged | Parts of marine structures |
| XS3 | Tidal, splash and spry zones | Parts of marine structures |

# Suitability Based on Slump and Compressive Strength

| Mix ID ($Na_2O$-MS) | Slump (mm) | Compressive strength (MPa) | | |
|---|---|---|---|---|
| | | 3d | 28d | 91d |
| 4%-0.75 | 55 | 22.3±0.1 | 44.7±0.2 | 46.4±1.0 |
| 4%-1.00 | 55 | 21.8±0.1 | 46.7±1.0 | 55.6±0.6 |
| 4%-1.50 | 55 | 1.7±0.0 | 49.5±0.2 | 52.6±2.3 |
| 4%-2.00 | 55 | 1.4±0.0 | 33.3±0.4 | 44.1±0.1 |
| 6%-0.75 | 65 | 31.7±0.7 | 47.3±0.0 | 51.8±2.4 |
| 6%-1.00 | 65 | 37.3±0.2 | 53.6±0.0 | 59.1±0.8 |
| 6%-1.50 | 65 | 20.3±0.7 | 60.8±0.1 | 67.4±2.6 |
| 6%-2.00 | 75 | 8.0±0.0 | 59.6±0.2 | 68.7±2.1 |
| 8%-0.75 | 70 | 32.3±0.0 | 51.9±0.1 | 56.2±0.2 |
| 8%-1.00 | 105 | 32.7±2.4 | 53.6±0.1 | 67.1±0.6 |
| 8%-1.50 | 145 | 34.1±0.7 | 59.3±3.2 | 70.5±2.5 |
| 8%-2.00 | 180 | 11.7±0.2 | 55.4±0.2 | 65.0±0.8 |
| PC | 50 | 35.4±1.2 | 58.9±1.8 | 66.3±2.3 |

**Slump Classes: S1 10-40mm; S2 40-90mm; S3 100-150mm; S4 160-210mm**
**Strength Classes: XS1 C37, XS2 C45, XS3 C45, XD1 C37, XD2 C37 and XD3 C45:**

# Suitability Based on $D_{nssm}$, pH, Corrosion Rate and $S^{2-}$

| Mix ID ($Na_2O$-MS) | $D_{nnsd}$ ($x\ 10^{-12}\ m^2/s$) | pH (use 11 for qualifaction) | Corrosion Rate (mm/year) | $S^{2-}$ (ppm) |
|---|---|---|---|---|
| 4%-0.75 | 6.59 | 11.7 | 0.020 | 2458 |
| 4%-1.00 | 4.25 | 11.9 | 0.025 | 1953 |
| 4%-1.50 | 2.54 | 10.5 | 0.019 | 3786 |
| 4%-2.00 | 4.14 | 9.9 | 0.010 | 4348 |
| 6%-0.75 | 3.07 | 11.9 | 0.011 | 5661 |
| 6%-1.00 | 3.18 | 11.9 | 0.014 | 6210 |
| 6%-1.50 | 2.01 | 11.4 | 0.009 | 6245 |
| 6%-2.00 | 3.76 | 9.9 | 0.010 | 6292 |
| 8%-0.75 | 2.24 | 12.4 | 0.012 | 664.0 |
| 8%-1.00 | 2.58 | 12.2 | 0.015 | 590.0 |
| 8%-1.50 | 1.88 | 10.8 | 0.011 | 618.3 |
| 8%-2.00 | 3.26 | 11.9 | 0.030 | 608.0 |
| PC | 9.70 | 12.5 | 0.012 | 329.6 |

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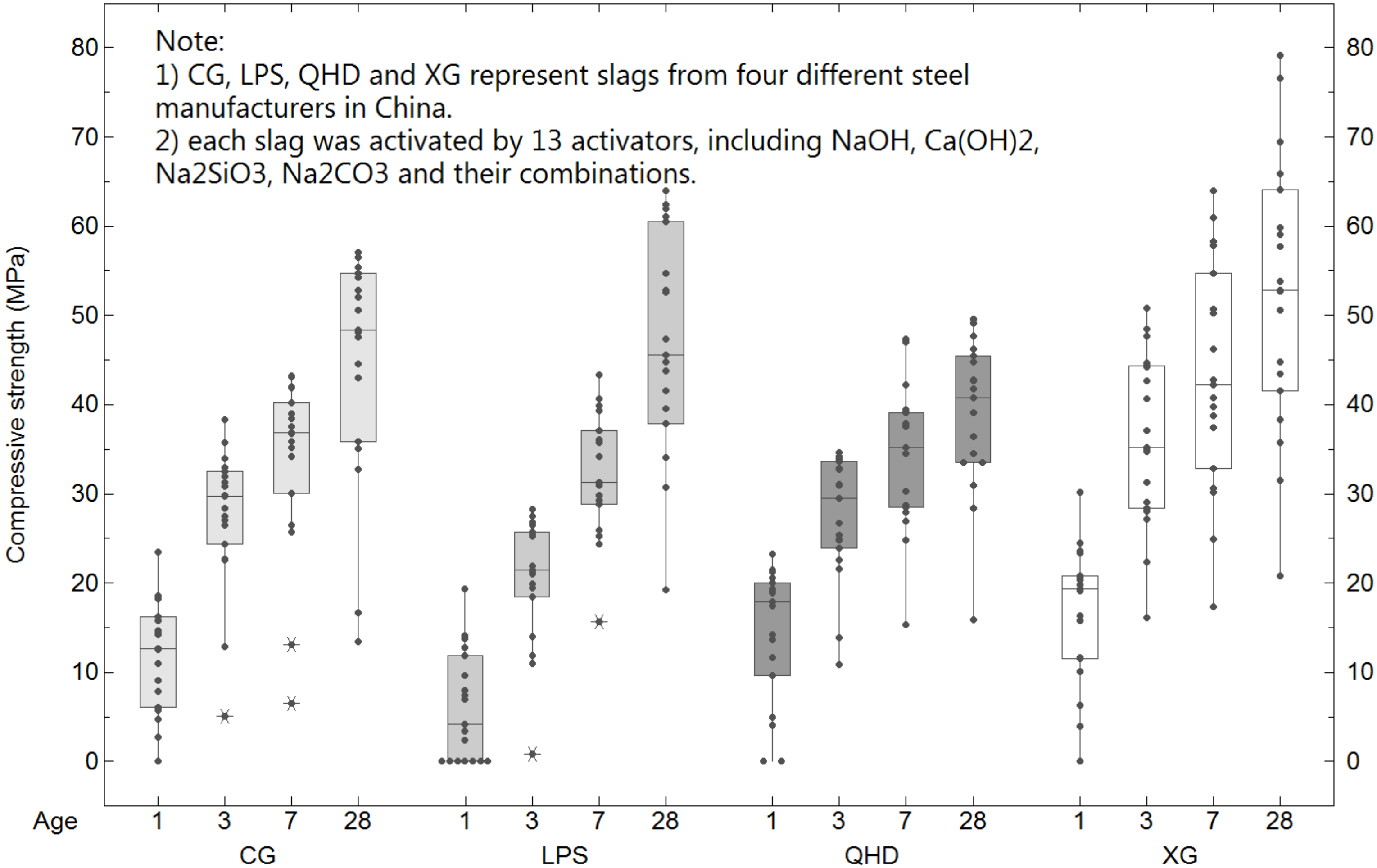
# Conclusions

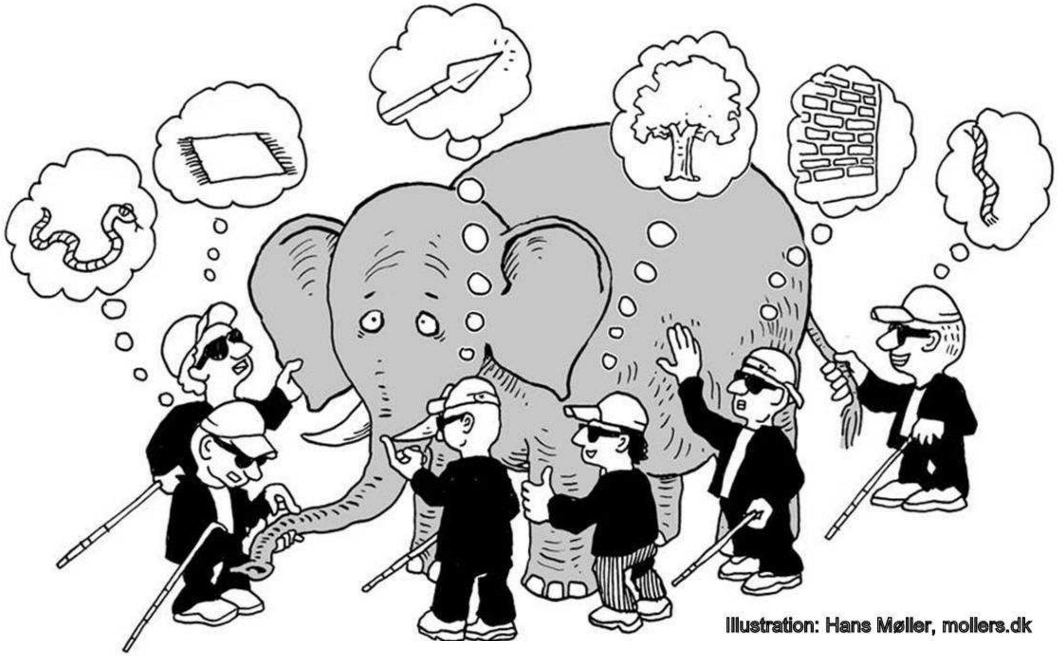
1. Compared to PC concrete, the AAS concretes achieved lower non-steady state diffusion coefficient.
2. The lower chloride diffusivity was accompanied by higher electrical resistivity, but not in all cases by lower rate of corrosion.
3. The galvanic corrosion of steel in AAS concretes depended on a number of factors, including the concentration of sodium and the molar ratio of the water glass used as the activator.
4. It is important to ensure that there is no outward leaching of alkalis for AAS concretes to perform well in chloride exposure environments.

# Unpublished Data From an On-going Research



# Recommendation

**Further research on the influence of pore solution of AAS concretes on corrosion is needed before their widespread use in chloride environments.**




## Truth is an elephant

# Notification of a Forthcoming Event

## SIXTH INTERNATIONAL CONFERENCE ON DURABILITY OF CONCRETE STRUCTURES (ICDCS2018)

## &

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# Thank You

**Any Questions?**

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