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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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**Changhui Yang (Chongqing University, China)**

**Yun Bai (University College London, 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<sub>2</sub> emission cement (CO<sub>2</sub> 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)

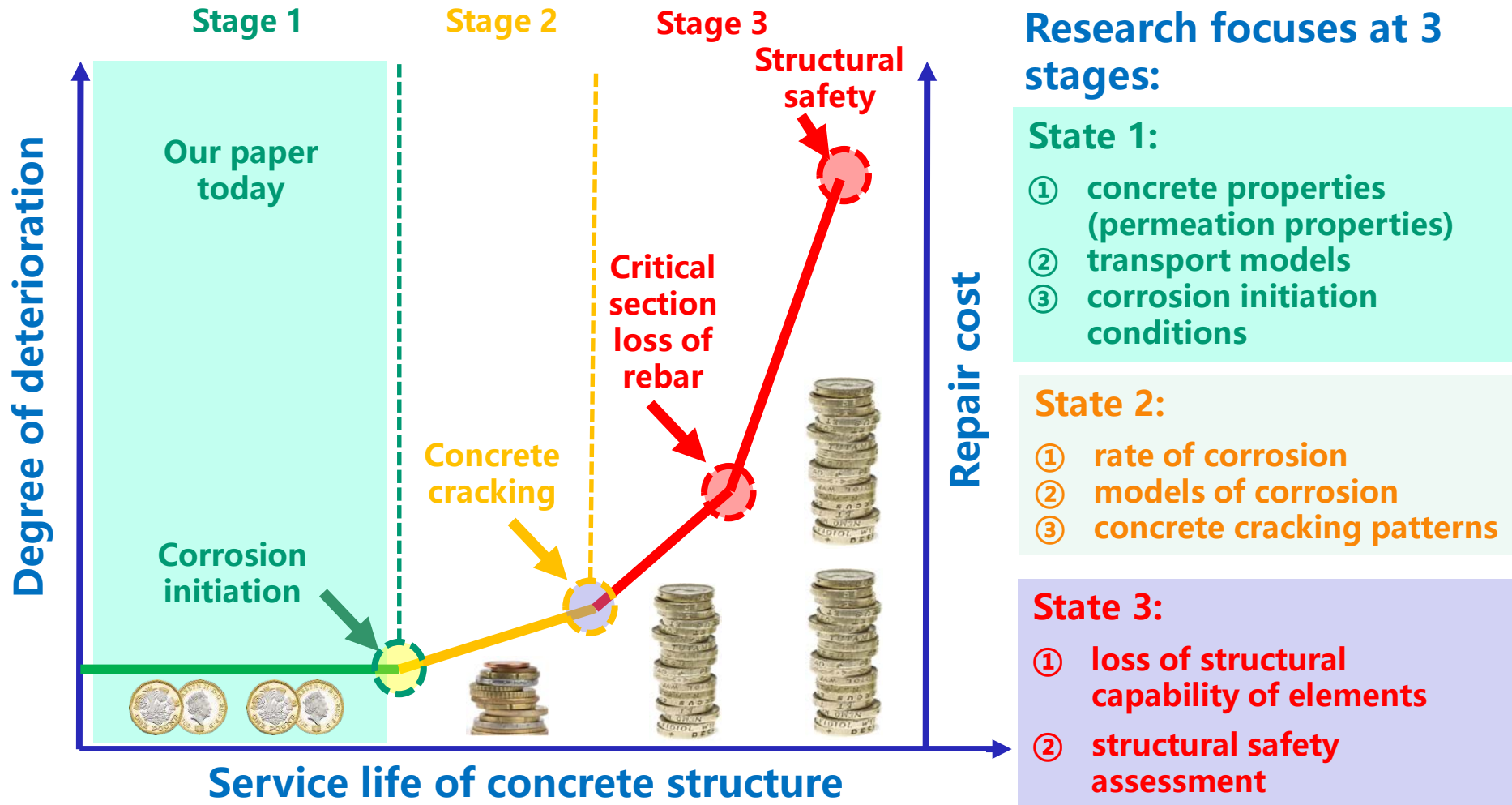


Precast walls  
(AU)

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



## 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

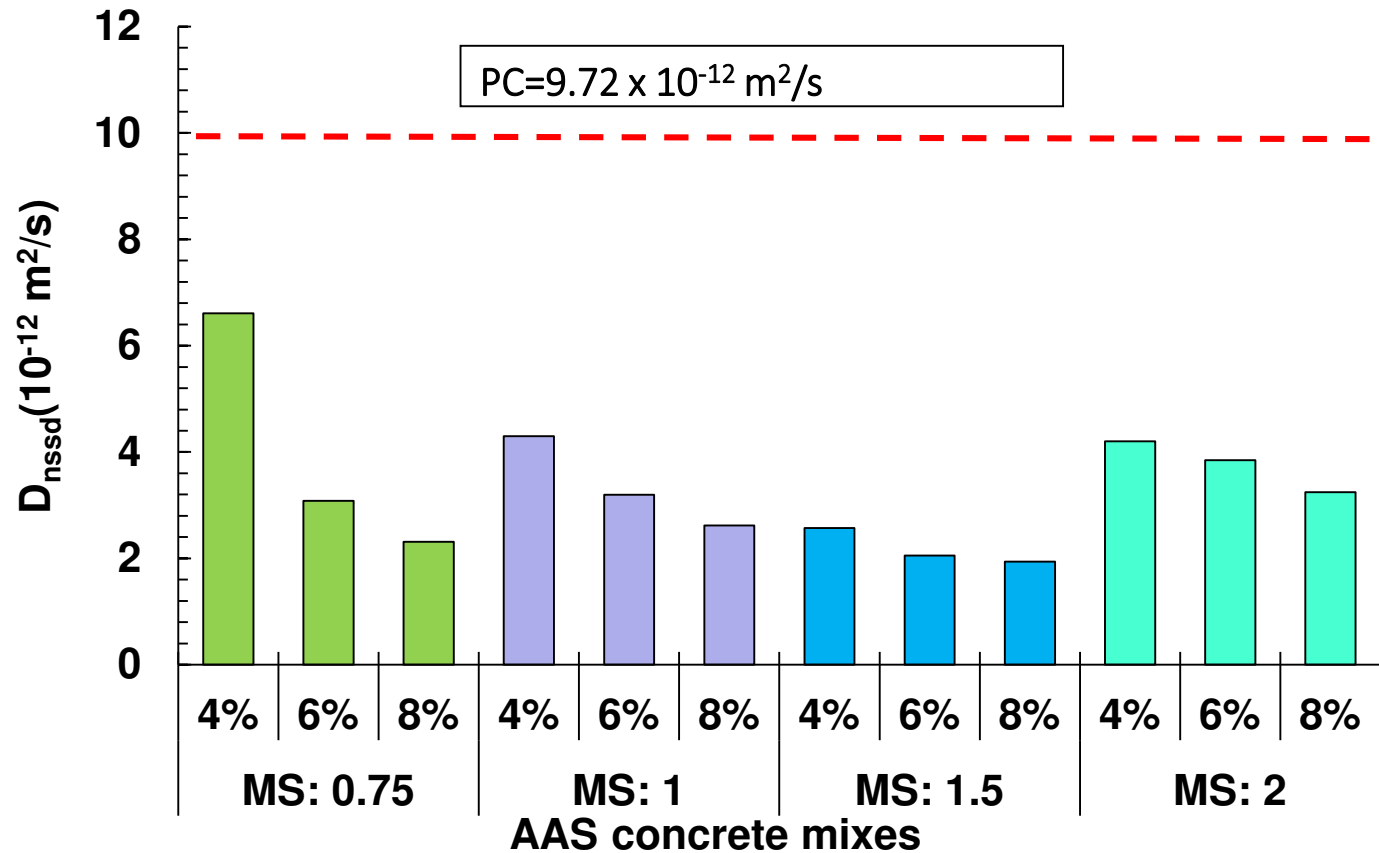
Mix NO (Na <sub>2</sub> O-MS)	Na <sub>2</sub> O (%)	Ms	Binder (kg/m <sup>3</sup> )	Sodium silicate (kg/m <sup>3</sup> )	NaOH (kg/m <sup>3</sup> )	Retarder (kg/m <sup>3</sup> )	Sand (kg/m <sup>3</sup> )	Coarse aggregate (kg/m <sup>3</sup> )
4%-0.75	4	0.75	371	34.6	13.6	1.11	654	1163
4%-1.00		1.00	368	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

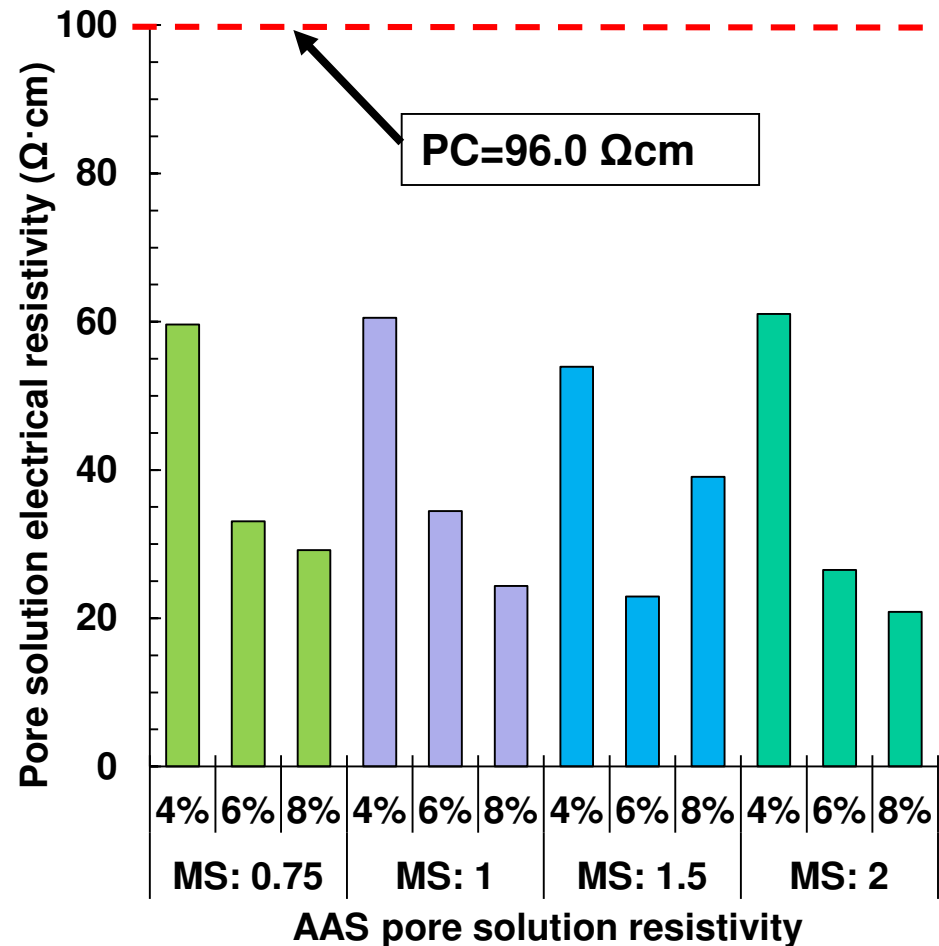
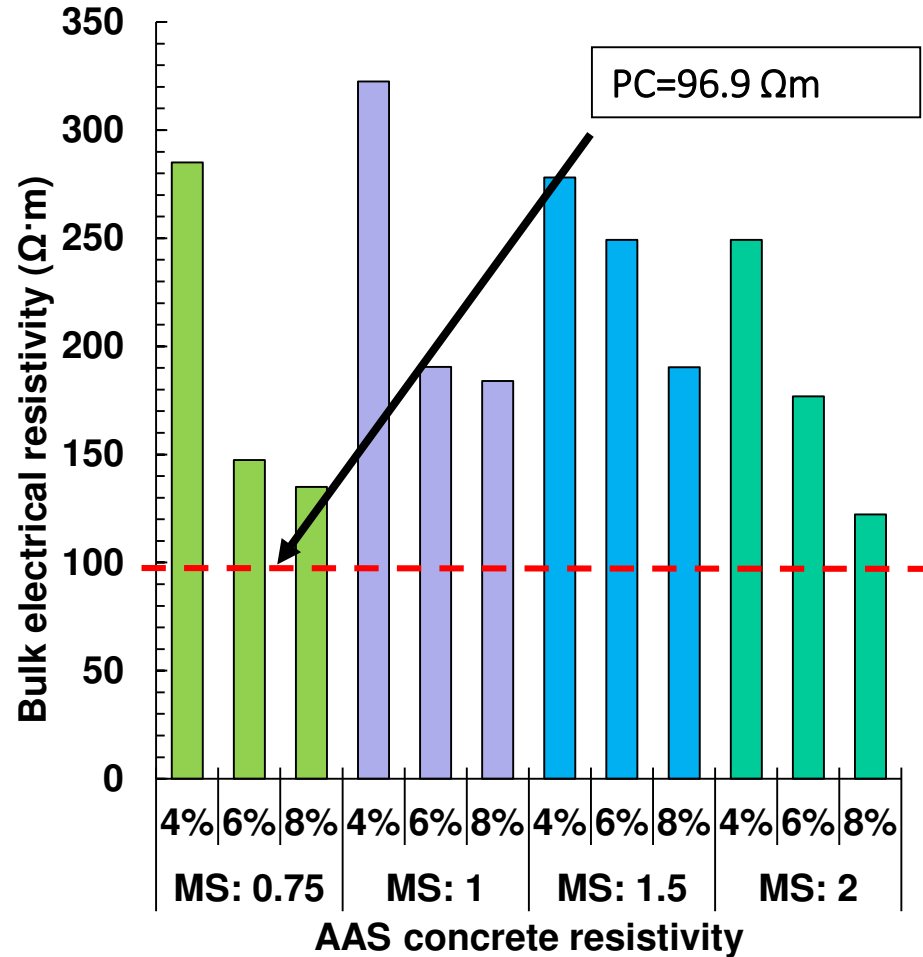
## Properties Measured and Test Methods Used: Part 1: Chloride Resistance of AAS Concretes

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<sup>+</sup> and S<sup>2-</sup> of the Pore Solution of AAS Concretes

Mix ID (Na <sub>2</sub> O-MS)	pH	Na <sup>+</sup> (ppm)	S <sup>2-</sup> (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 vs Different parameters	Diffusivity of AAS concrete Electricity of AAS concrete Na <sup>+</sup> in pore solution S <sup>2-</sup> in pore solution

## Test Setup to Study Corrosion Resistance

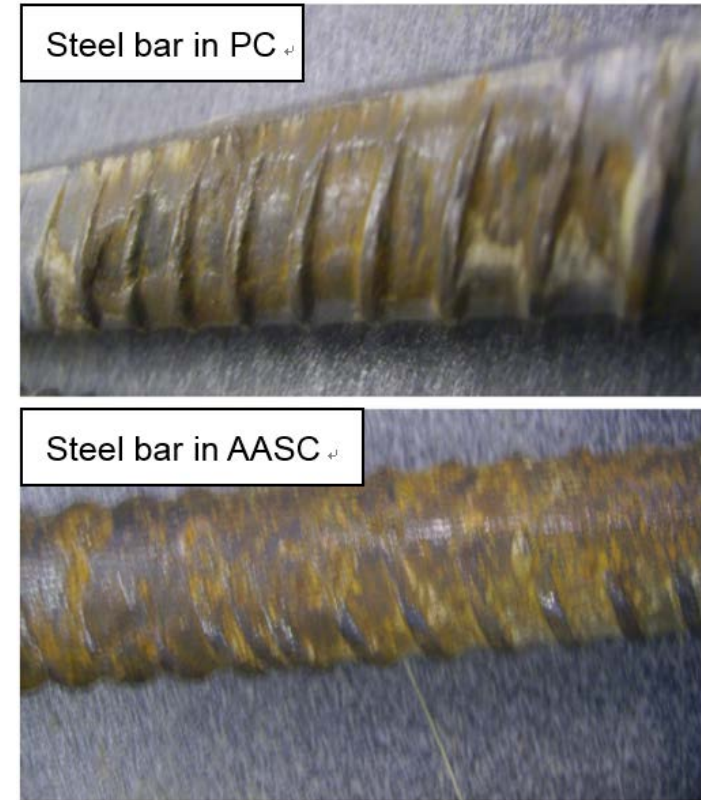
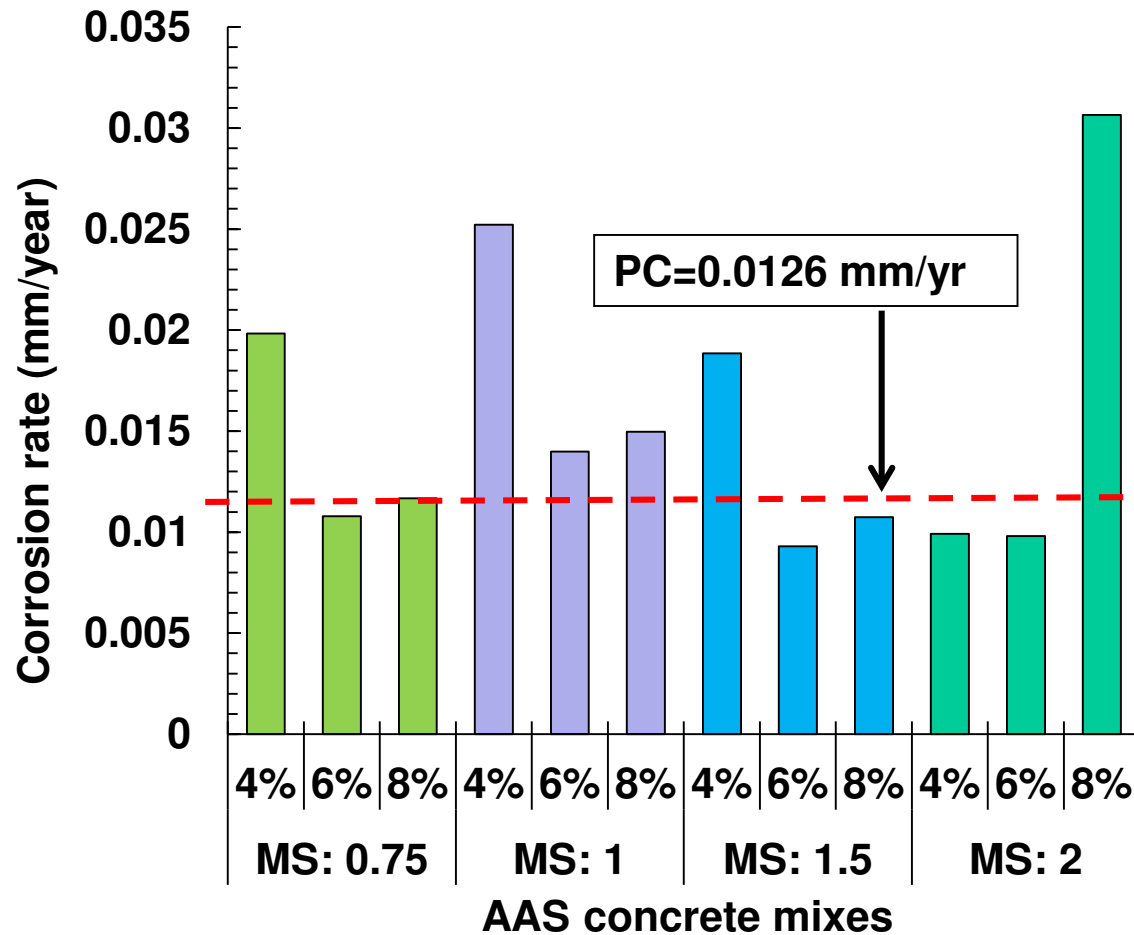


Stainless steel electrodes at 15mm, 25mm, 35mm and 45mm depths for electrical resistance measurements

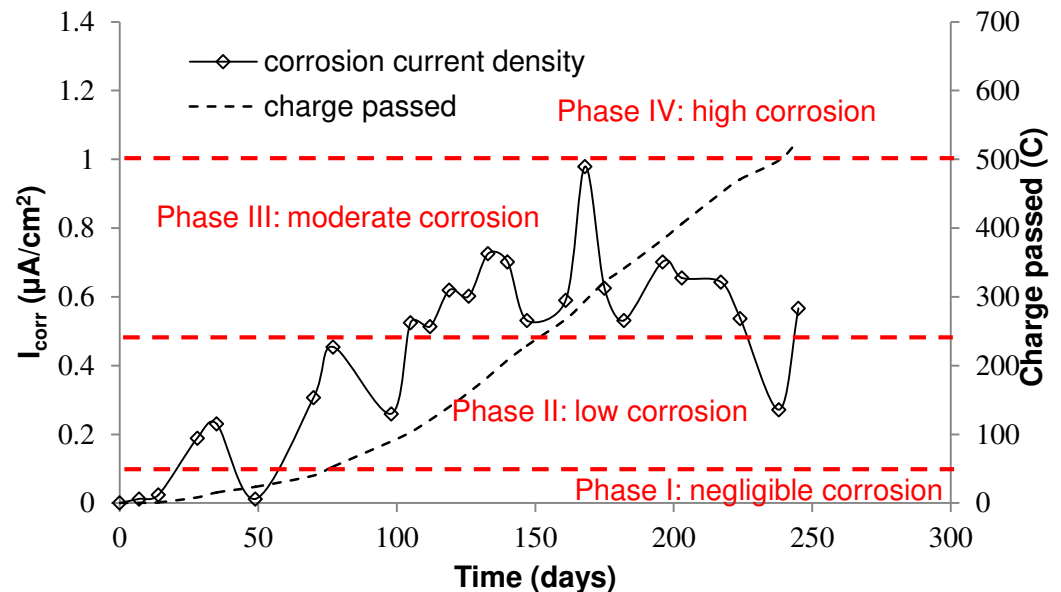
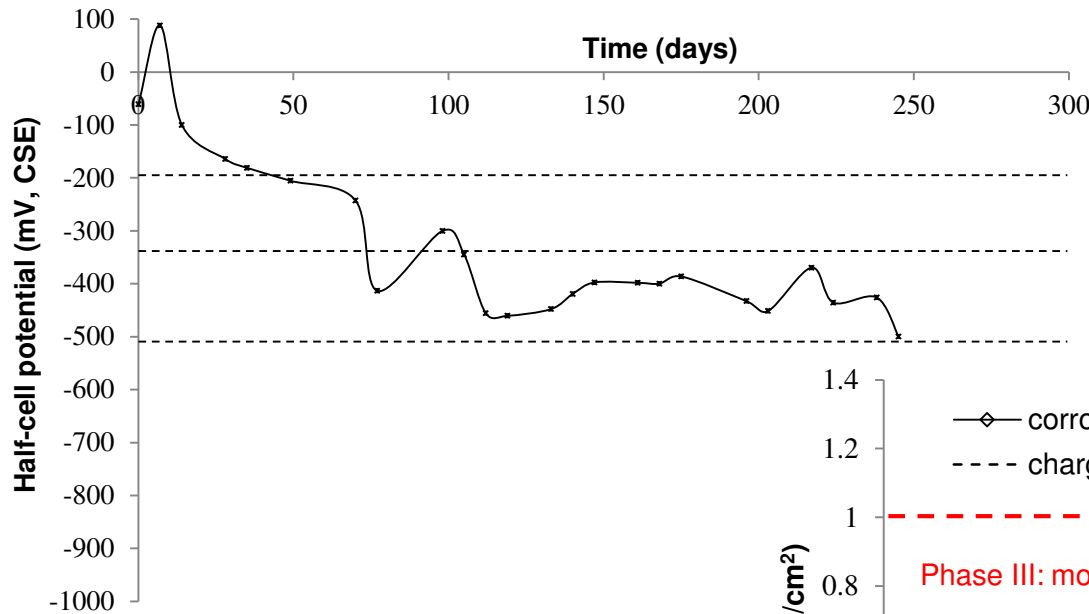
Top bar to act as anode and the bottom three bars together to act as cathode, connected by a  $10\Omega$  resistance

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

## Rate of Corrosion in AAS Concretes

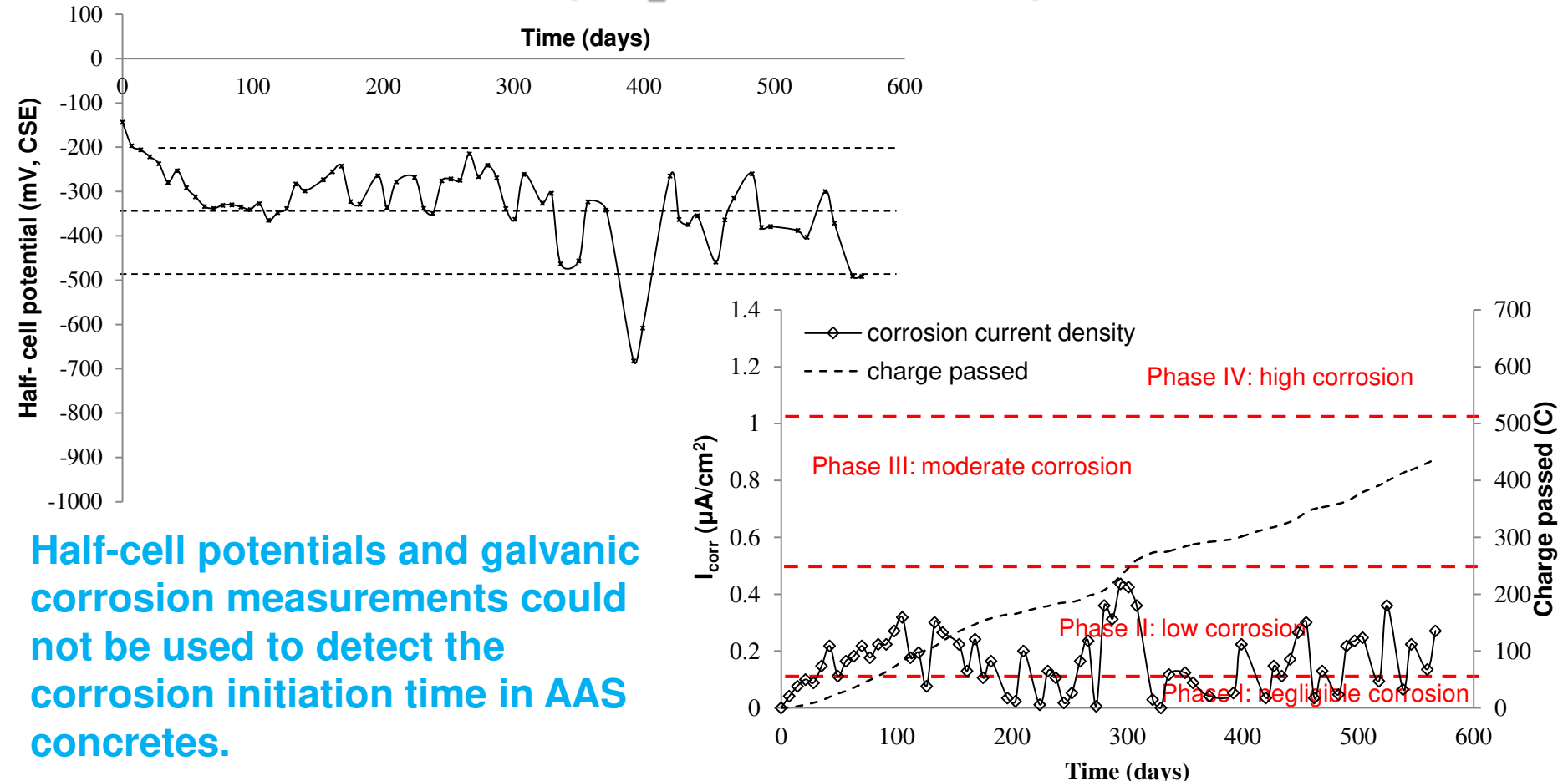


## Half-Cell Potentials and Galvanic Corrosion Data for PC



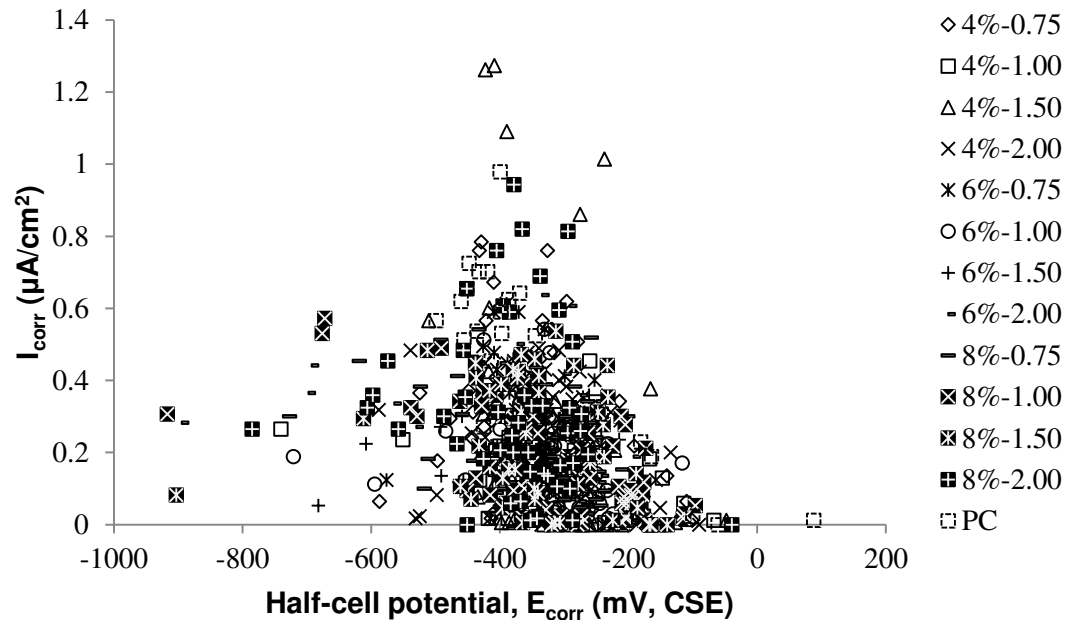
Both the half-cell potentials and galvanic corrosion measurements could be used to detect the corrosion initiation time in PC concretes.

## Half-Cell Potentials and Galvanic Corrosion Data for AASC ( $\text{Na}_2\text{O}\%$ : 6, $M_s$ : 5.0)

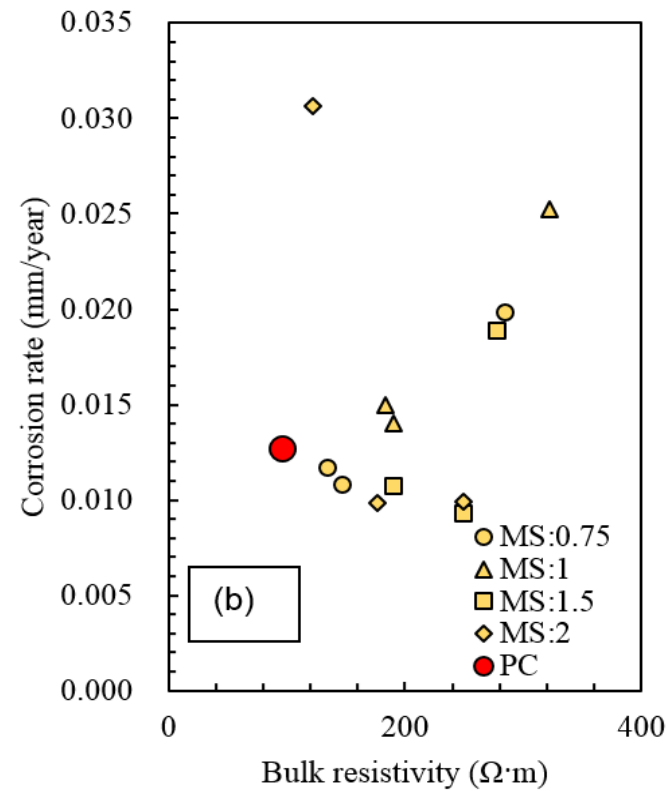
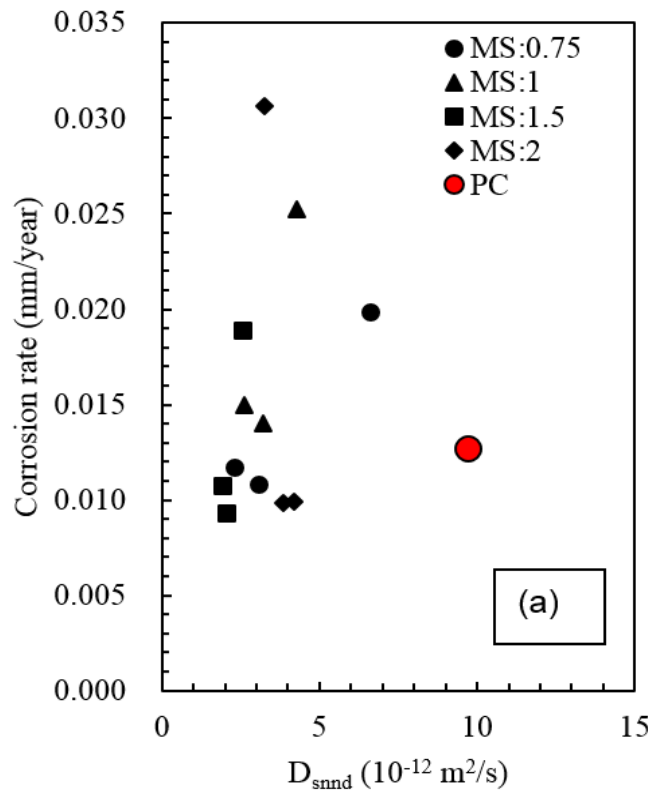


Half-cell potentials and galvanic corrosion measurements could not be used to detect the corrosion initiation time in AAS concretes.

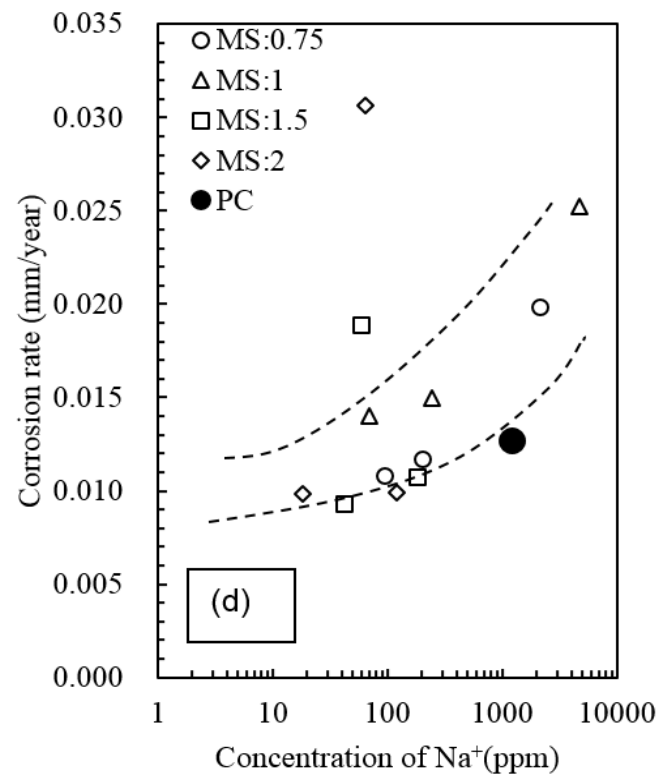
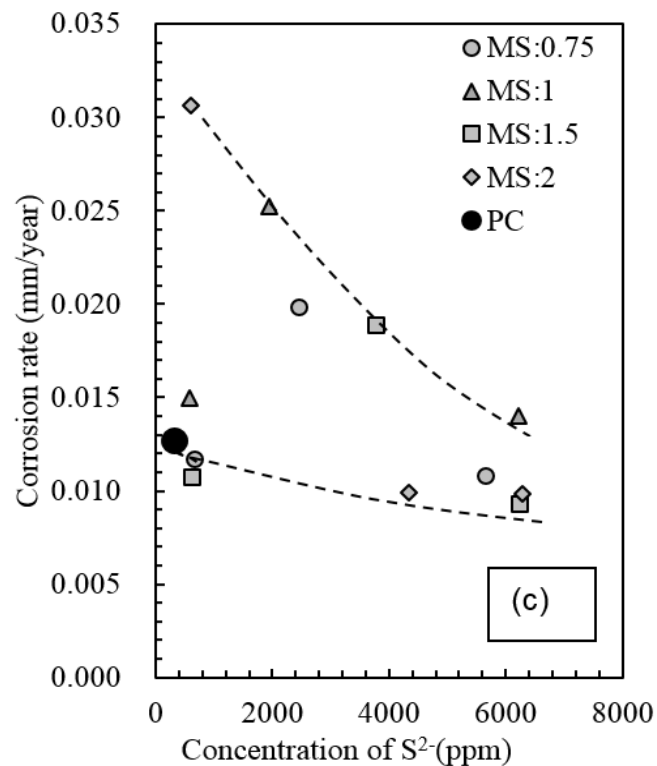
## Relationship Between Half-Cell Potentials and Galvanic Corrosion in AAS Concretes



## 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 spray zones	Parts of marine structures

## Suitability Based on Slump and Compressive Strength

Mix ID (Na <sub>2</sub> O-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	<b>33.3±0.4</b>	<b>44.1±0.1</b>
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 <sub>2</sub> O-MS)	$D_{nssd}$ (x 10 <sup>-12</sup> m <sup>2</sup> /s)	pH (use 11 for qualification)	Corrosion Rate (mm/year)	S <sup>2-</sup> (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

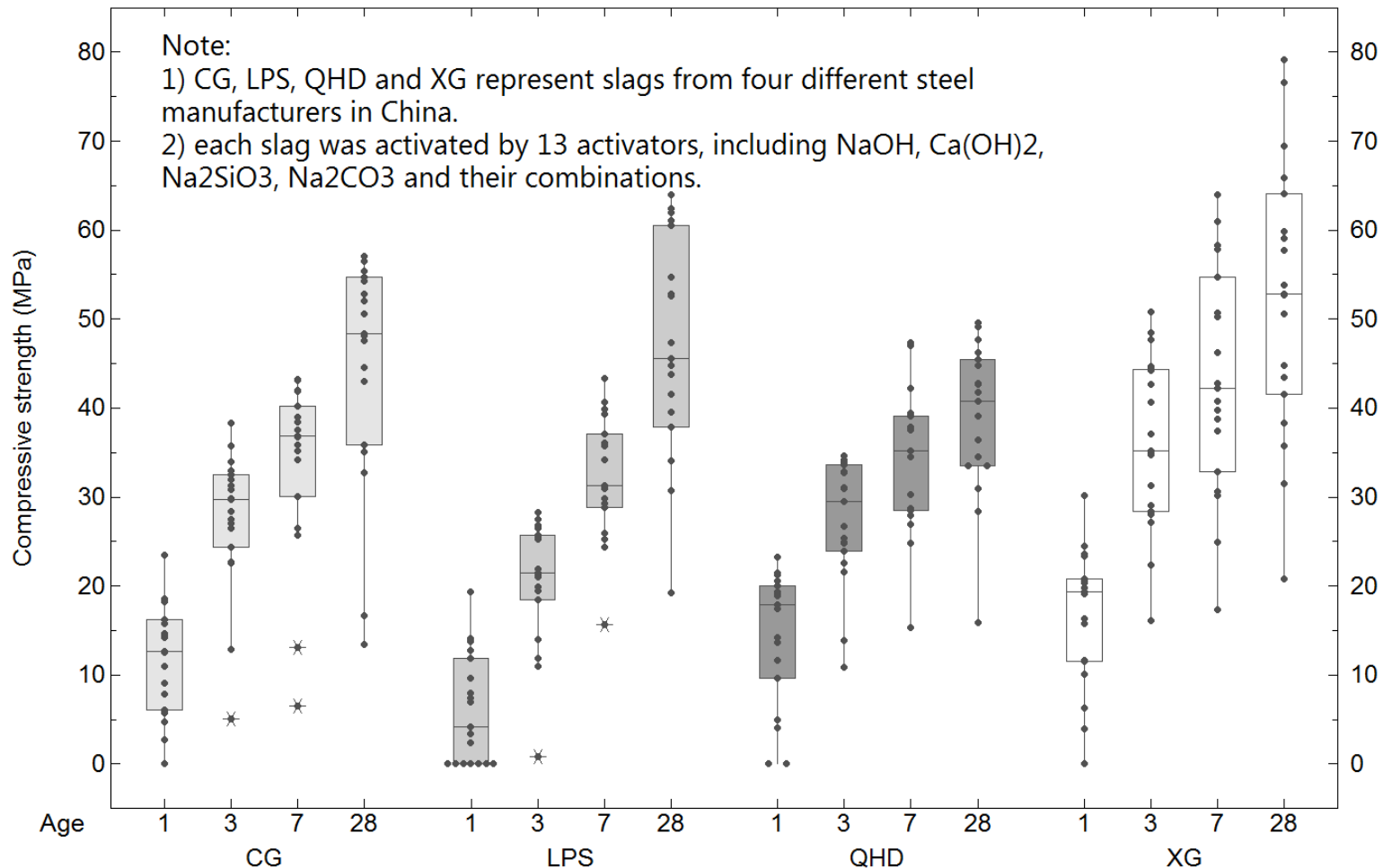
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## Conclusions

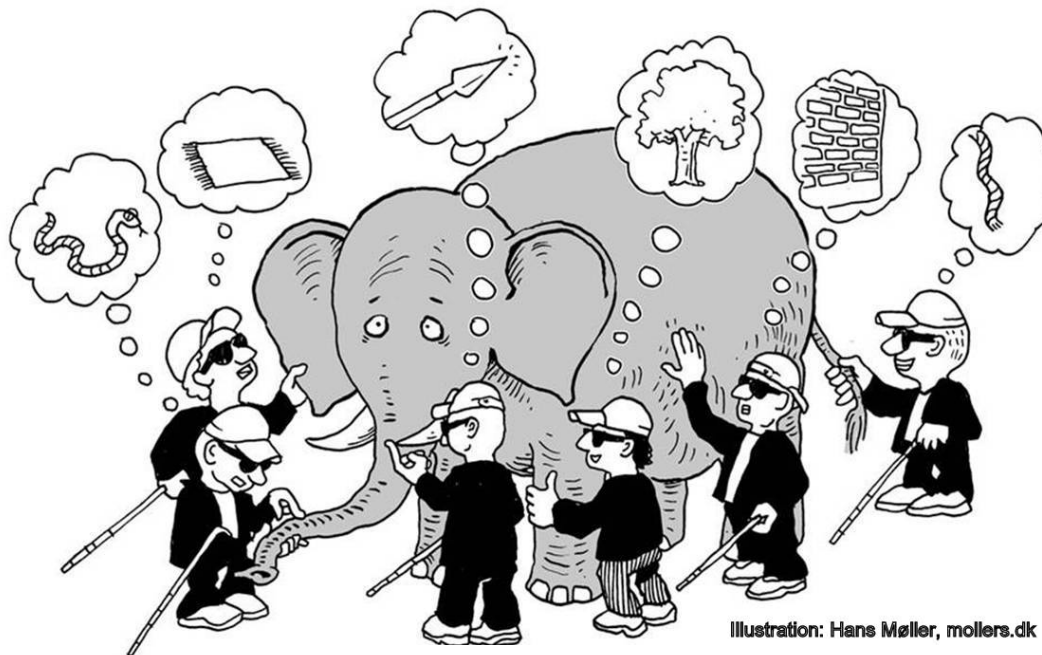
- 1. Compared to PC concrete, the AAS concretes achieved lower non-steady state diffusion coefficient.**
- 2. The lower chloride diffusivity was accompanied by higher electrical resistivity, but not in all cases by lower rate of corrosion.**
- 3. The galvanic corrosion of steel in AAS concretes depended 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

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**&**

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**15<sup>th</sup> – 17<sup>th</sup> May 2018, Edinburgh, UK**

## Thank You

### Any Questions?

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