Galvanic Corrosion Control of Reinforced Concrete: Lessons Learnt from 20 Years of Site Trials

Icorr, Aberdeen Branch

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VECTOR CORROSION TECHNOLOGIES
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20-Year Galvanic Anode Data

Background of Galvashield Technology

- Original XP Anodes
- 20-Year Results
- Lessons Learned
- Aging Factor
- Enhanced Design Considerations
- Fusion™ Technology

20-Year Galvanic Anode Data

Cathodic or Corrosion Prevention

- Purpose is to prevent corrosion from initiating in chloride-contaminated environment
- No existing criterion with regard to potential shift
- Current density necessary to prevent corrosion from initiating is 0.4 to 2 mA/m^2, much lower than amount necessary to stop on-going corrosion activity

20-Year Galvanic Anode Data

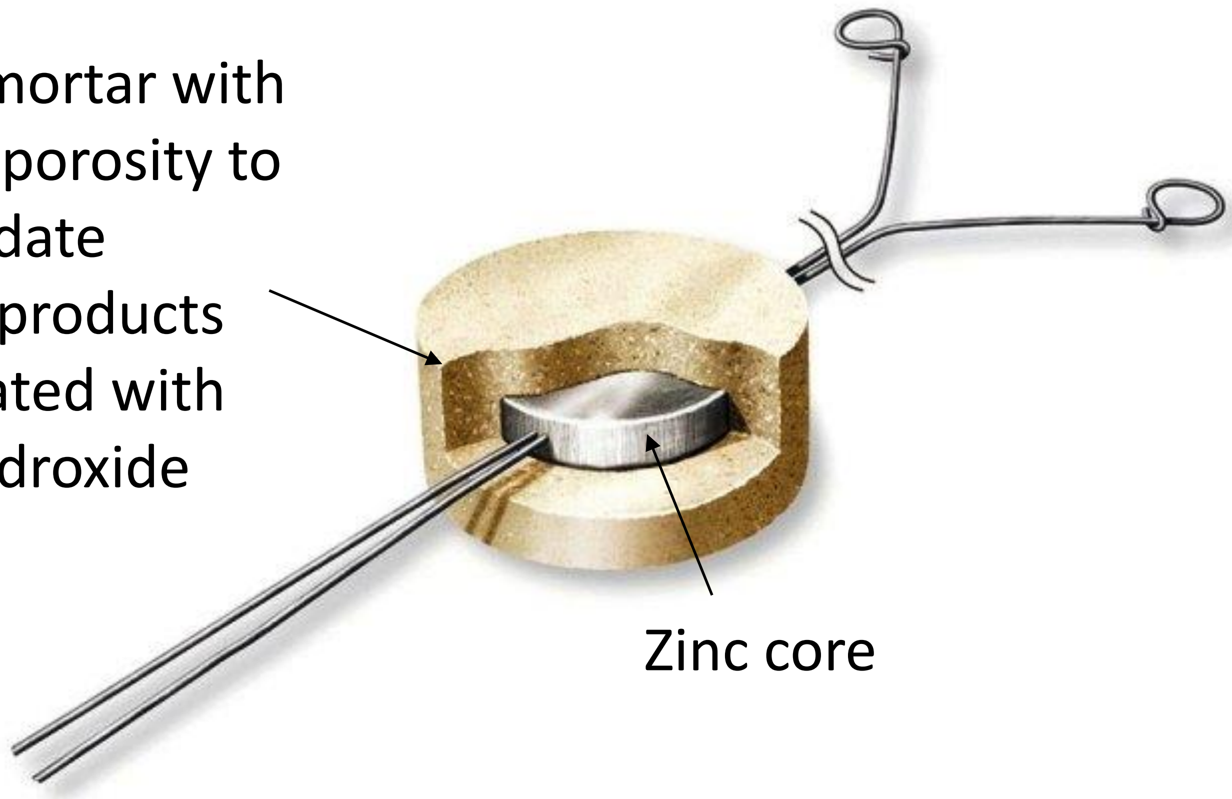
Incipient anode formation

(Chasing the repairs!)

20-Year Galvanic Anode Data

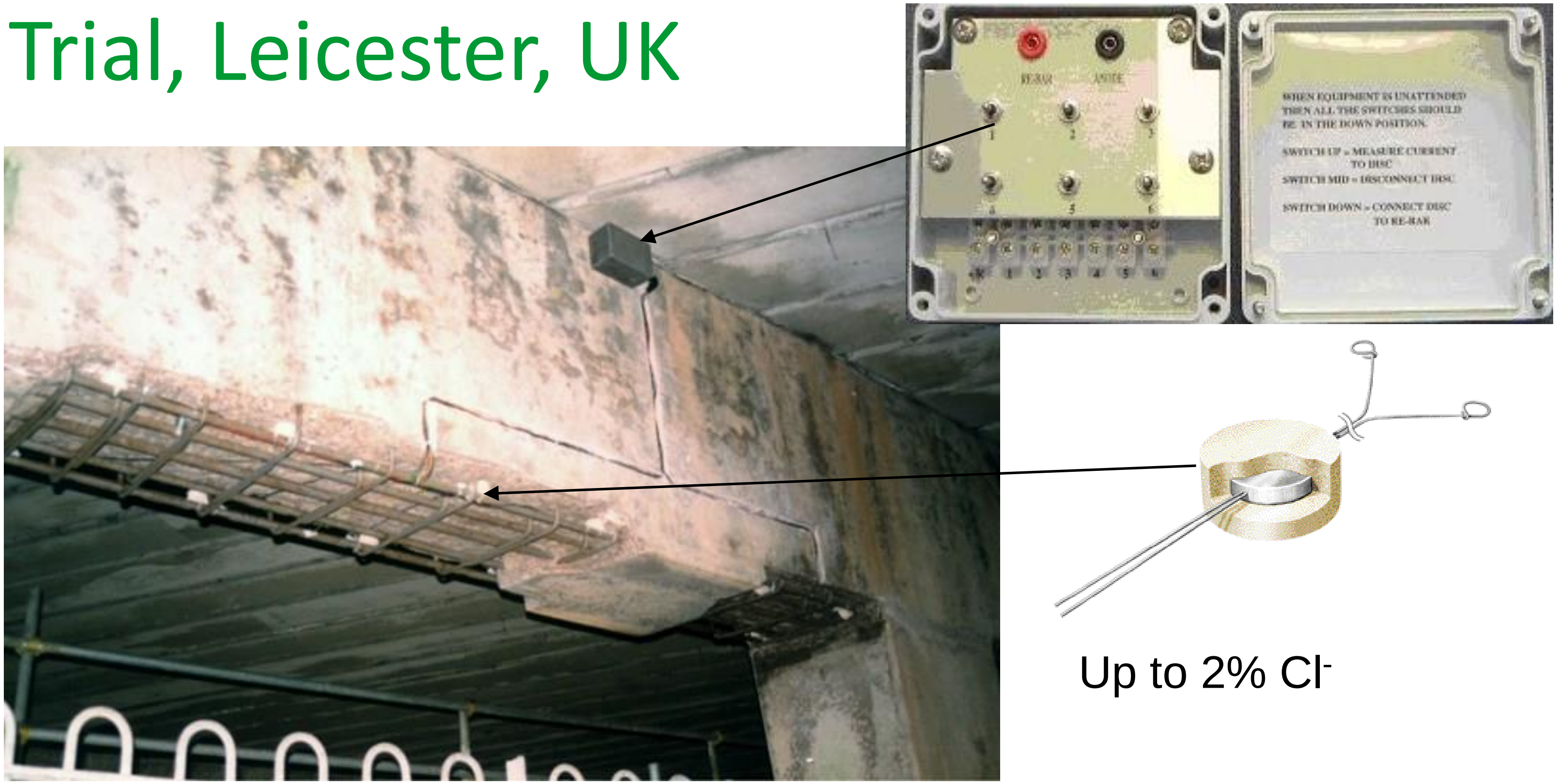
Installation of anodes

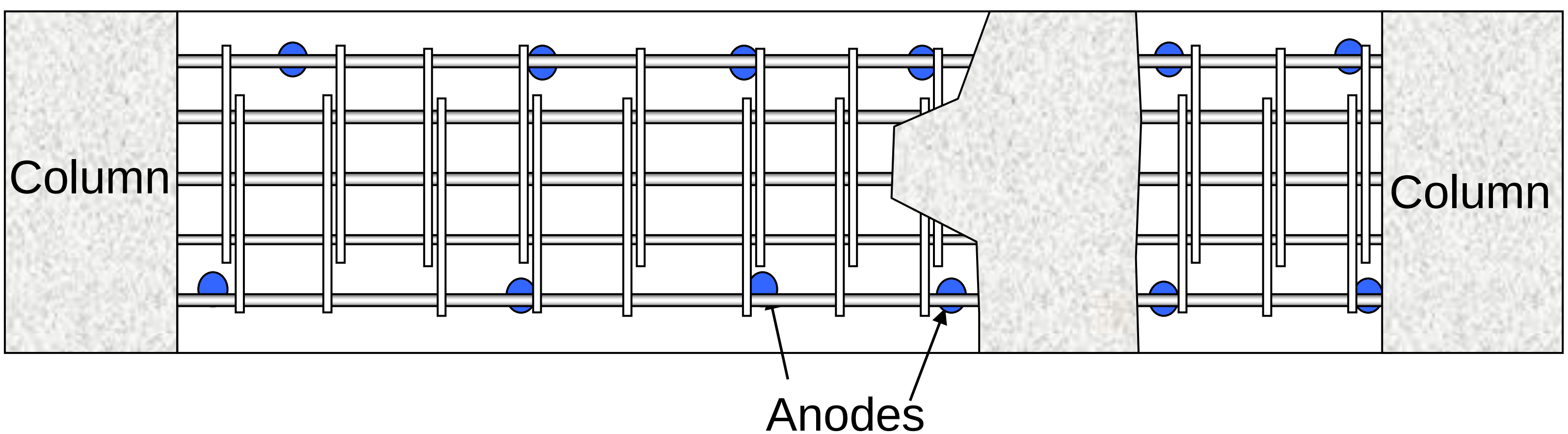
20-Year Galvanic Anode Data



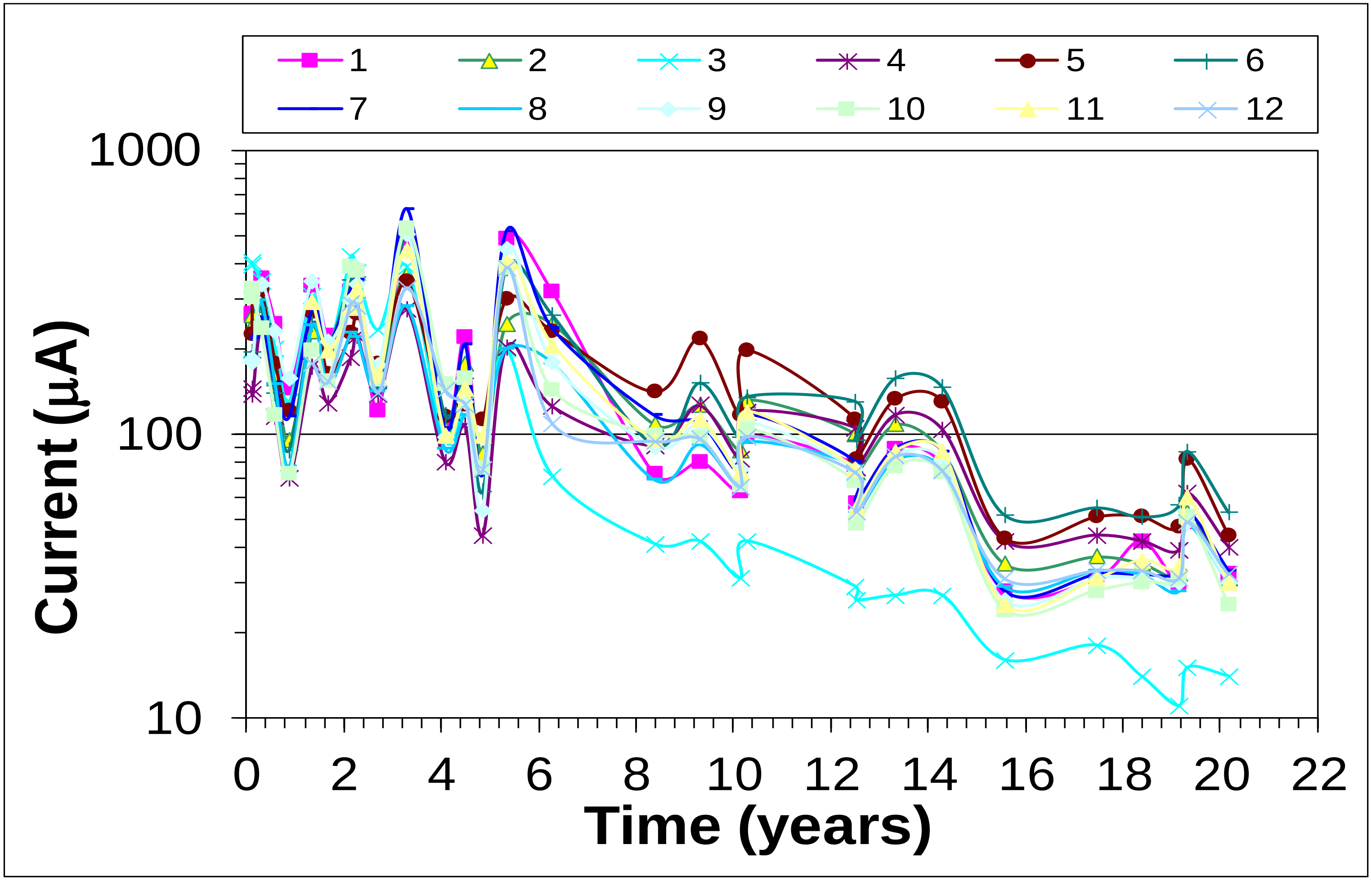
Basic 10-Year Design Anode

Site Trial, Leicester, UK



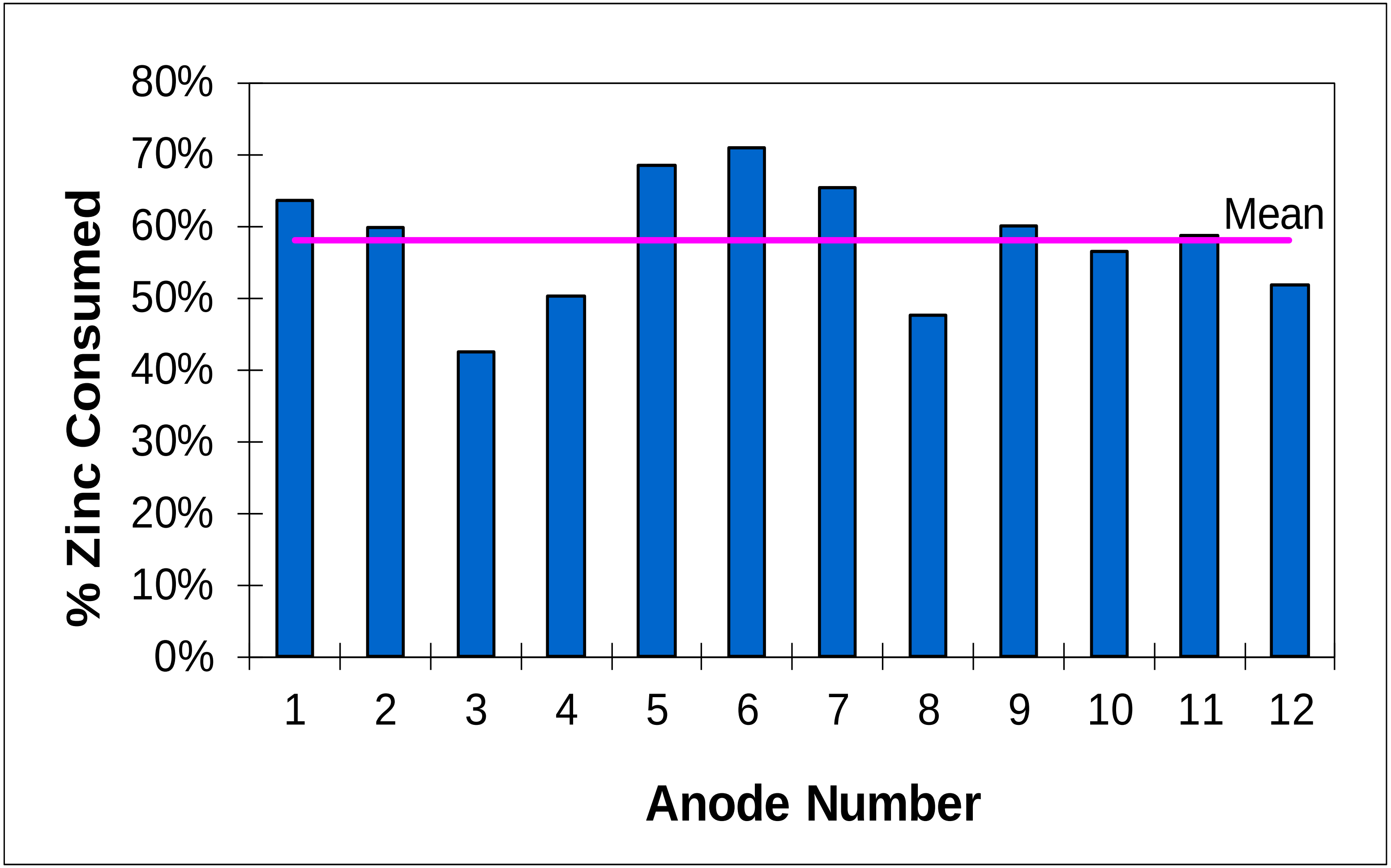


Site Trial, Leicester, UK



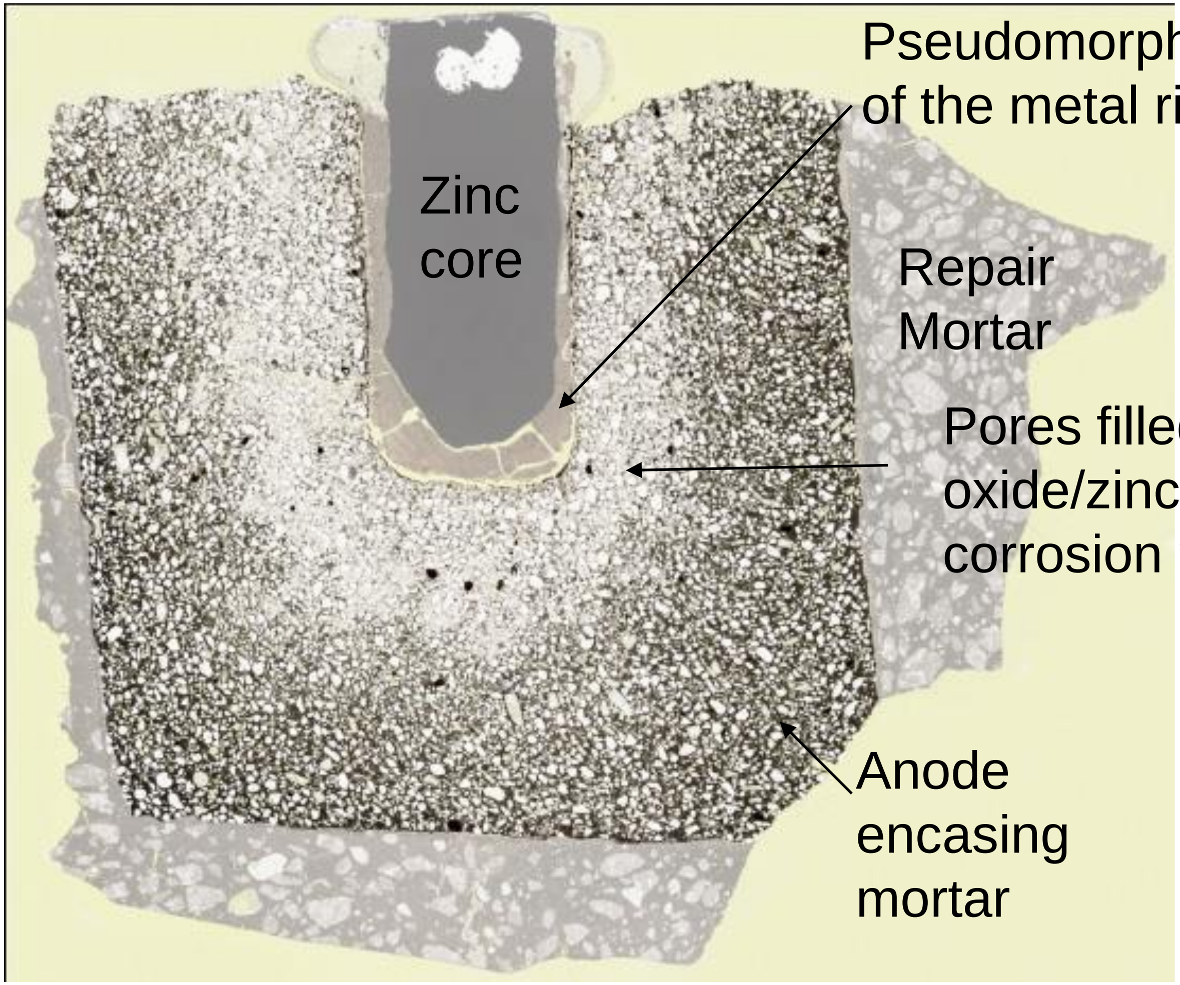
Current with time of individual anodes

Site Trial, Leicester, UK



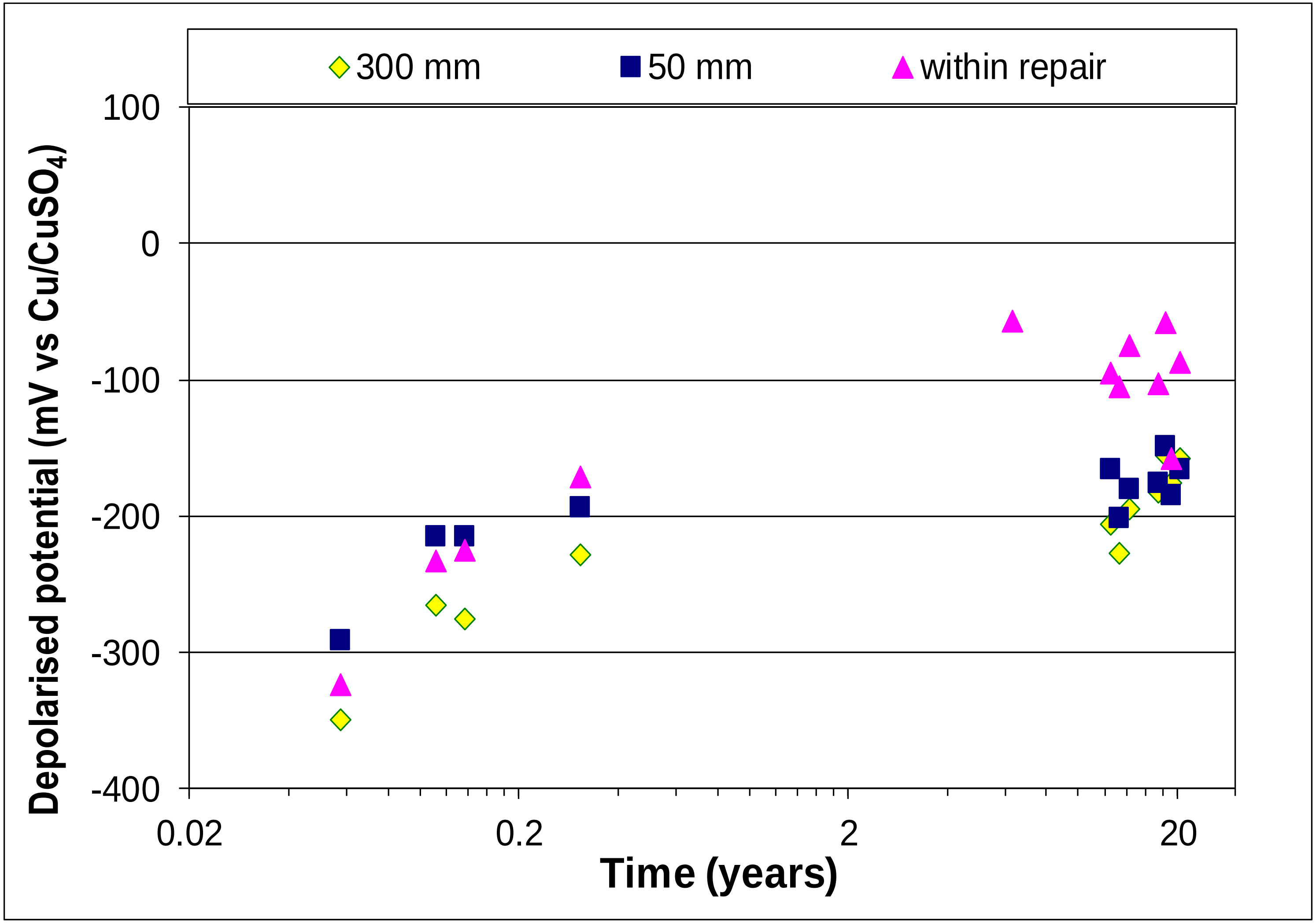
Zinc consumption of individual anodes after 20 years

Site Trial, Leicester, UK



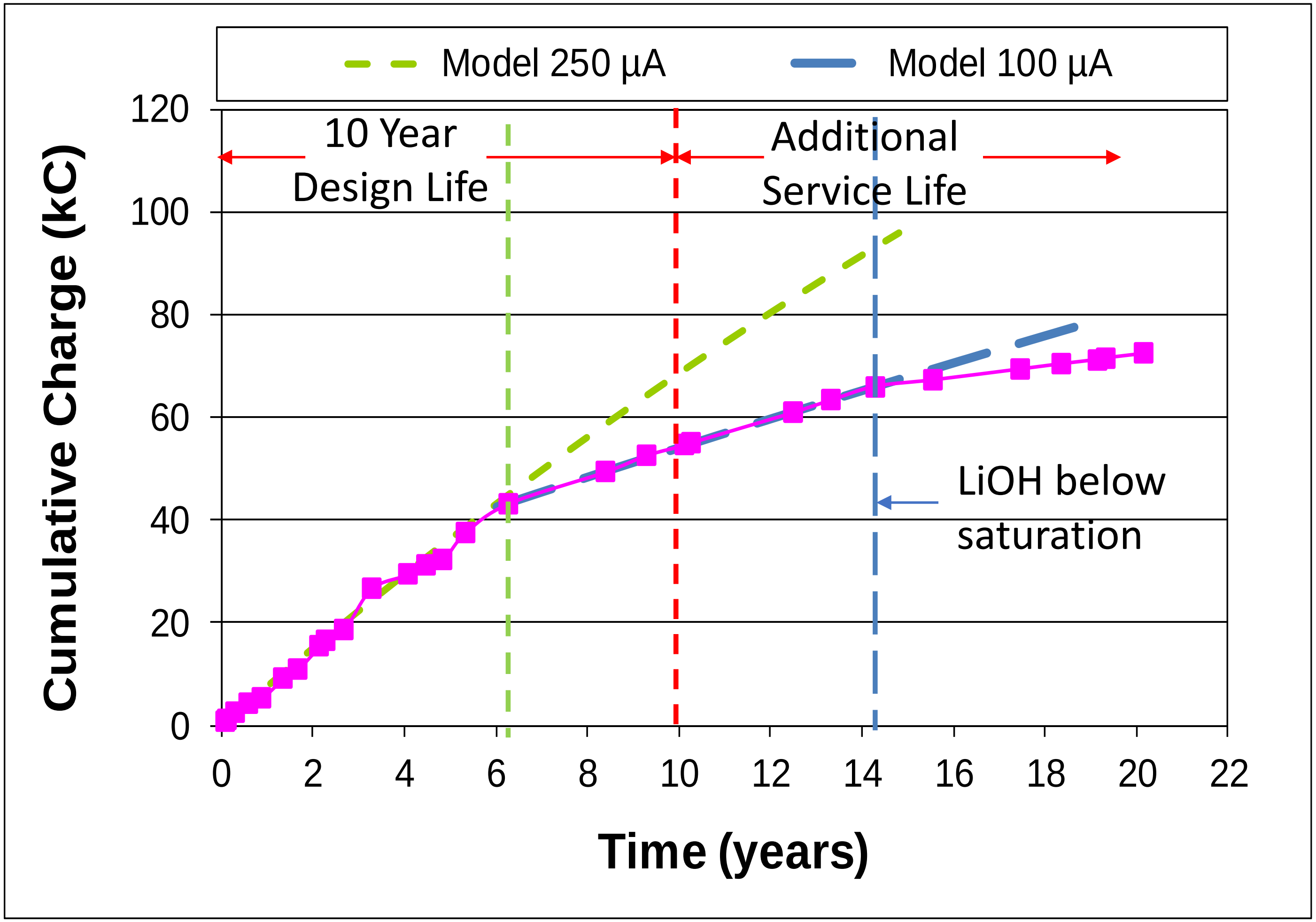
Cross Section of anode after 10 years

Site Trial, Leicester, UK



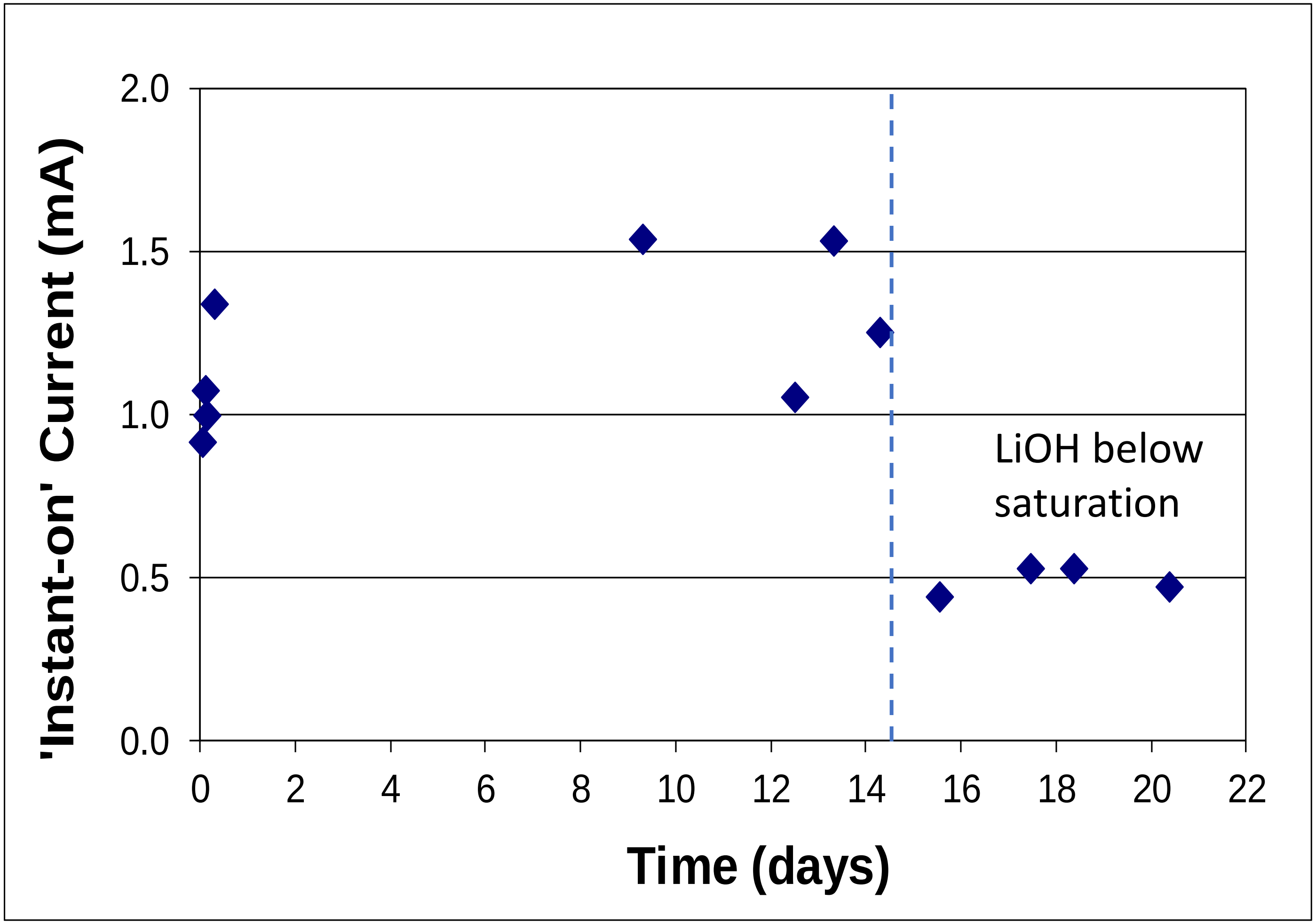
Mean depolarised potential with time

Site Trial, Leicester, UK



Cumulative charge from anodes with time

Site Trial, Leicester, UK



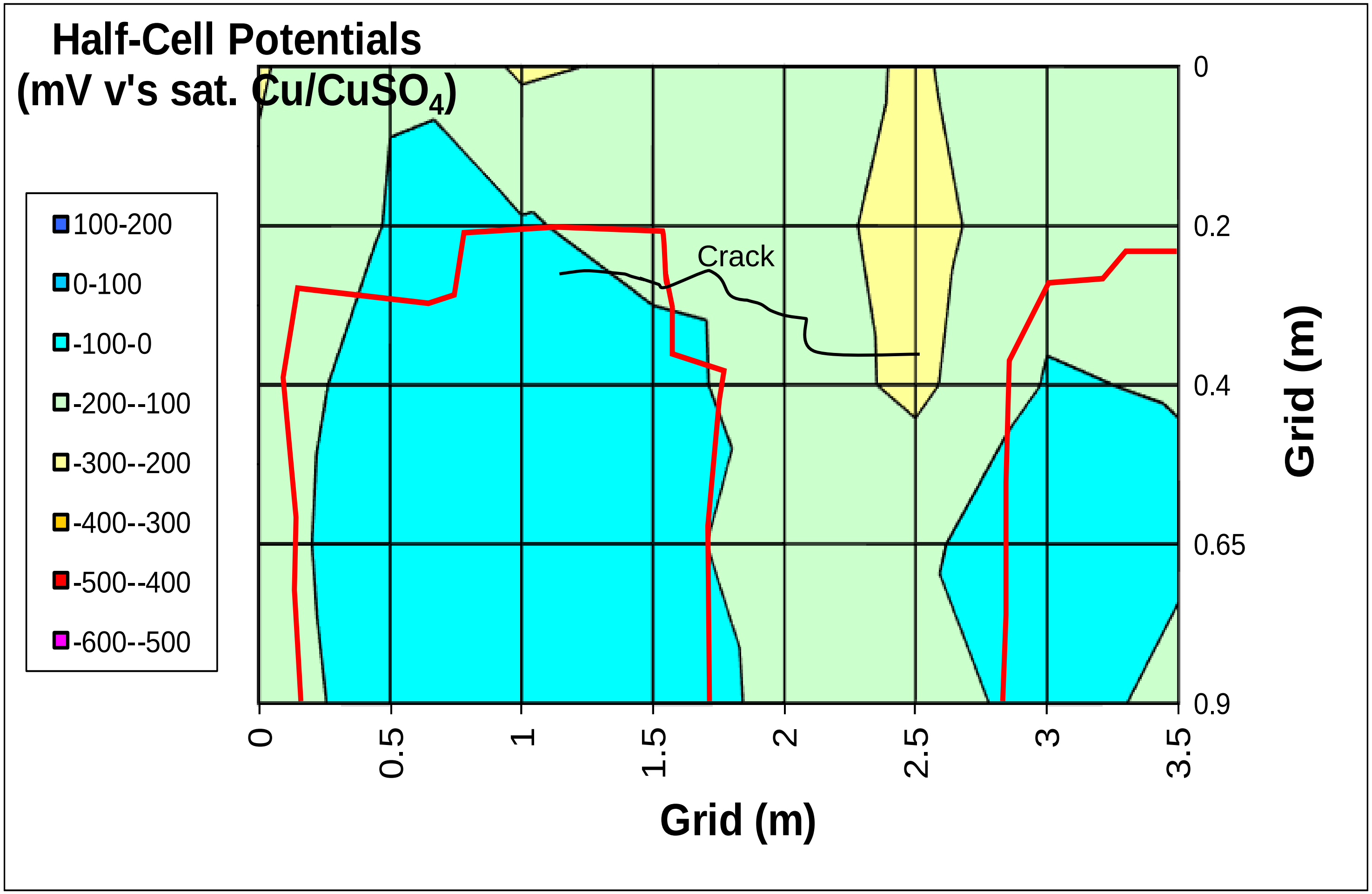
Mean “instant-on” current of anodes

Site Trial, Leicester, UK

Condition of anode after 20 years

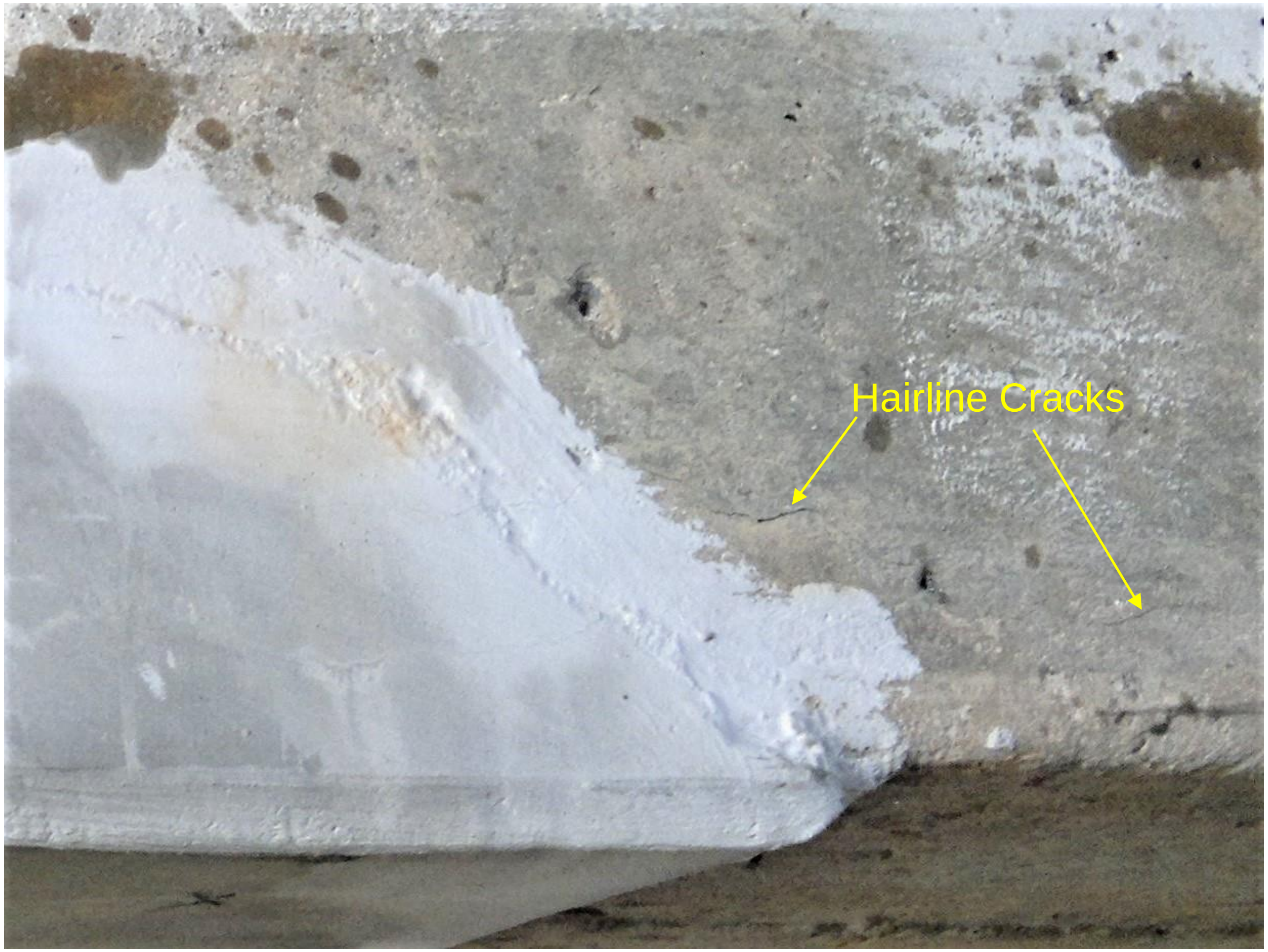
Anode after corrosion products removed

Site Trial, Leicester, UK



Potential map after 20 years

Site Trial, Leicester, UK

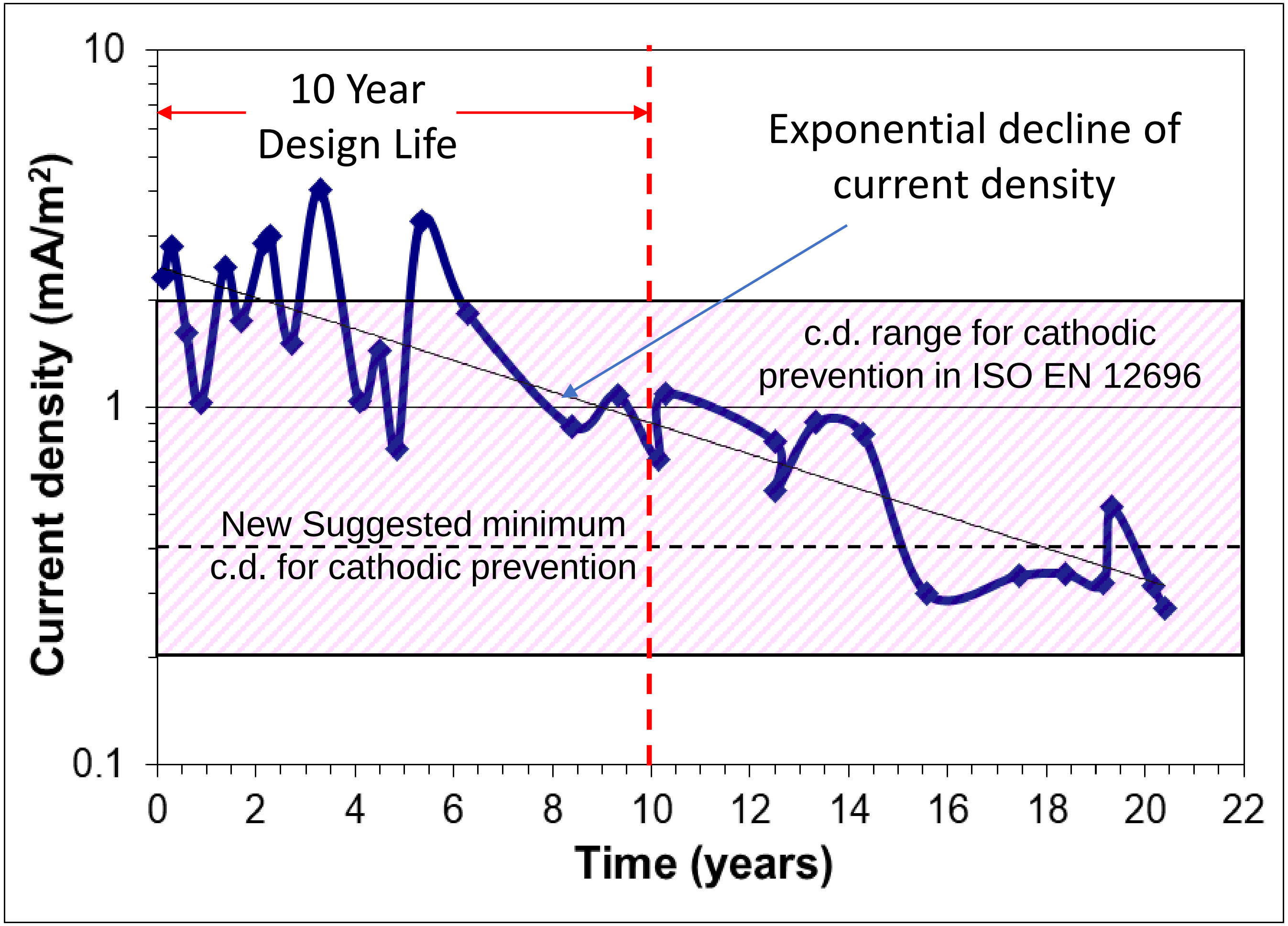


Fine cracking after 15 years

Site Trial, Leicester, UK

Enlarged cracking after 20 years

Site Trial, Leicester, UK



Mean Current density of anodes up to 20 years

Galvanic Anode Monitoring – Lessons Learnt

- Exponential decline of current density consistent with "Half-Life" principle
- Current density halves every 7 years a term described as "Aging-Factor"
- Humidity and particularly temperature, modify current output significantly

Galvanic Anode Monitoring – Aging Factor

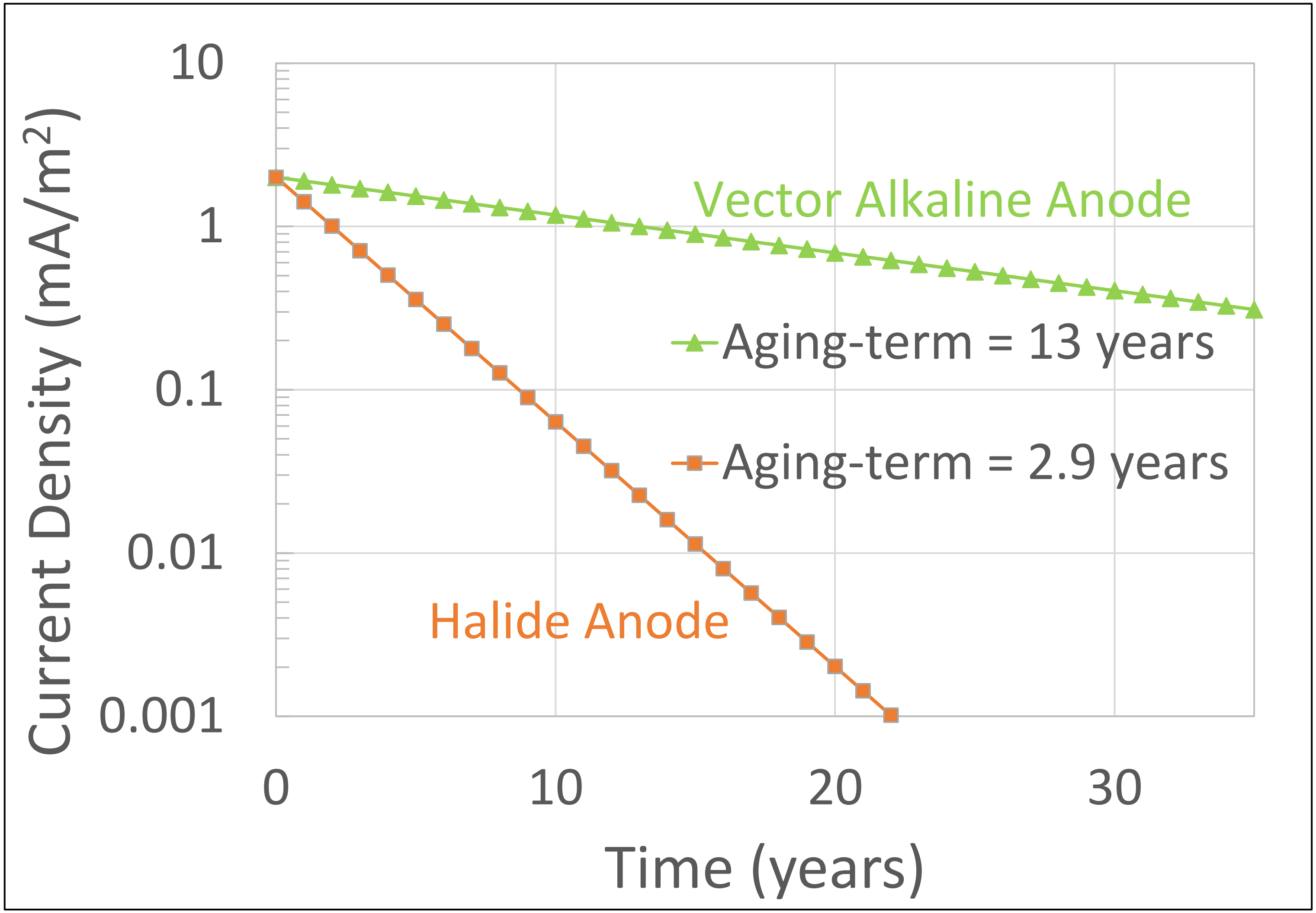
Anode type and size $t_{1/2}$	Site Location/ Concrete Element	Initial current per anode (mA)	Anode spacing (mm)	Aging Factor (Years)	Mean
X1- Repair	Leicester Crossbeam	0.25	600	6.9	
X1- Repair	Leicester Column-1	0.50	750	4.2	5.6
X1- Grid	India Slab	0.62	300	5.9	
X2- Repair	Leicester Column-2	0.26	300	12.6	
X2- Grid	India Slab	0.99	300	12.6	13.0
X2- Grid	M53 Abutment	0.29	300	13.9	
X4- Repair	Leicester Column-2	0.36	300	9.2	
X4- Grid	India Slab	2.22	300	10.5	10.3
X4- Grid	M53 Abutment	0.55	300	10.5	
X4- Grid	Ivy St. Abutment	0.64	300	10.8	
Long Rod	Ohio Abutment			7.8	11.3
Long Rod	North Otter Bridge Deck			14.7	
Mean all				10.0	

Galvanic Anode Monitoring – Aging Factor

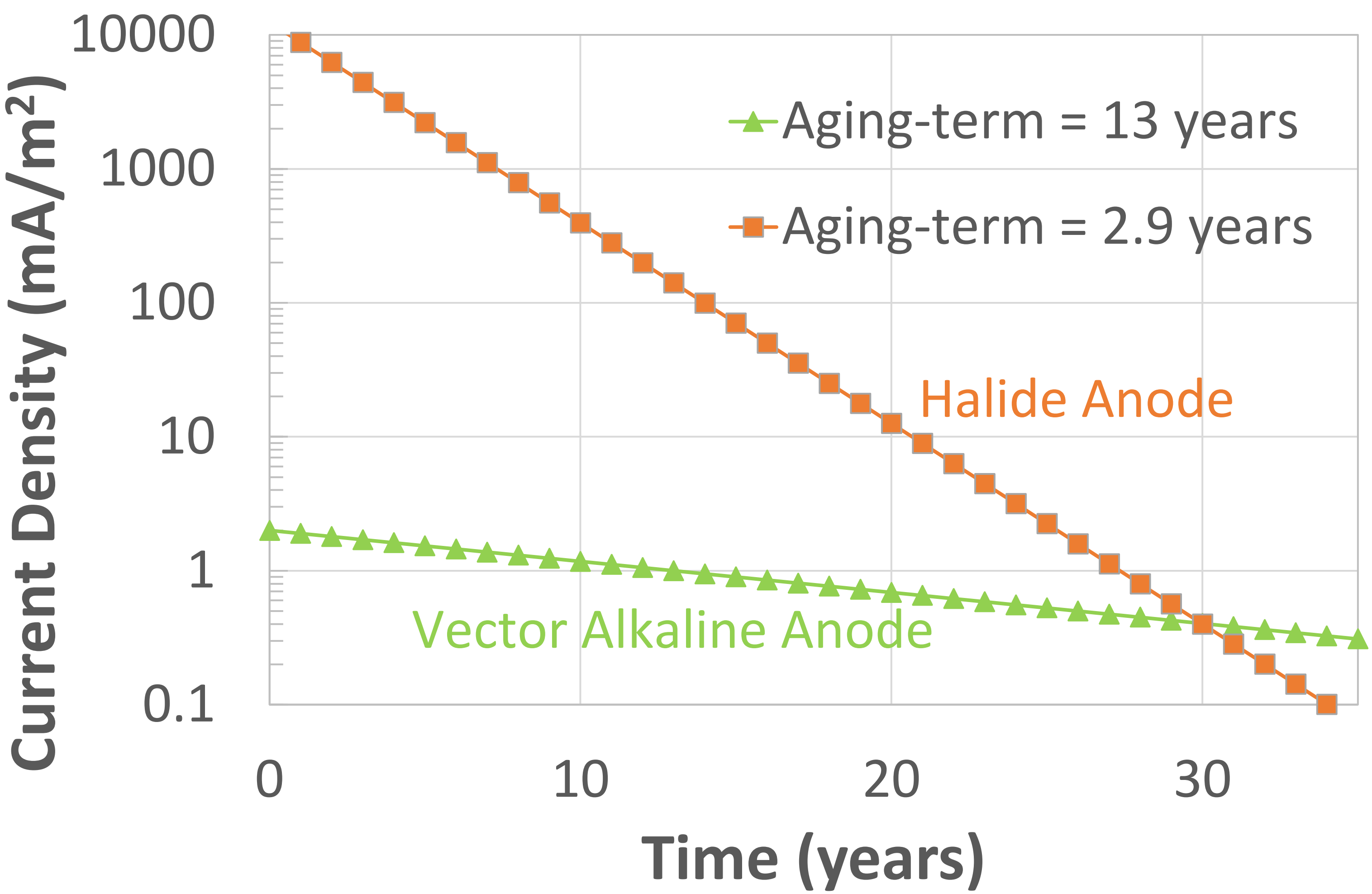
Halide Activated Anodes

Anode Type	Aging Factor (Years)	Reference
Point	2.9	Bewley
Point	1.3	Bennett & McCord

Galvanic Anode Monitoring – Design Considerations



Galvanic Anode Monitoring – Design Considerations



Summary

- Service life of existing galvanic anodes is expected to be at least 15 years and possibly 20-30 years
- Current output of galvanic anodes is sustained for many years with a gradual exponential drop at a measured rate (Aging Factor)
- The Aging Factor can be built into the design of the anode system to predict minimum service life
- Enough knowledge has now been gained about anode behaviour over time to allow design to any required level of steel protection

New Developments

Fusion™ Technology (Two Stage protection)

- Arrest Corrosion with Initial high charge using ICCP anodes
- Maintain passivity of steel long-term with galvanic elements

Effects of Steel Polarisation

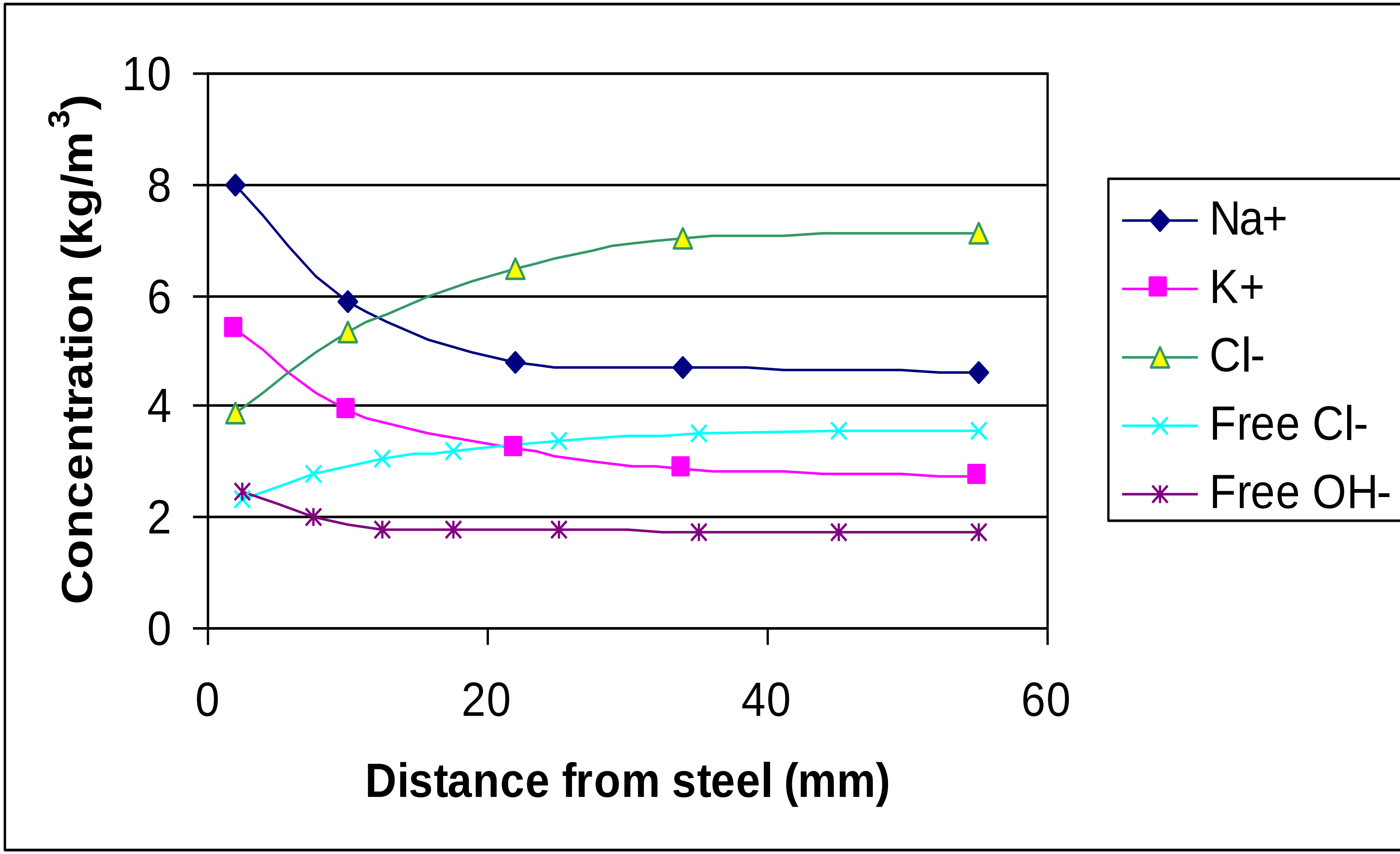
During steel polarisation (Cathodic Protection)

- Chloride ions move away from steel
- Hydroxyl ions are produced at the steel from the cathodic reaction:

$$\tfrac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2(OH^-)$$

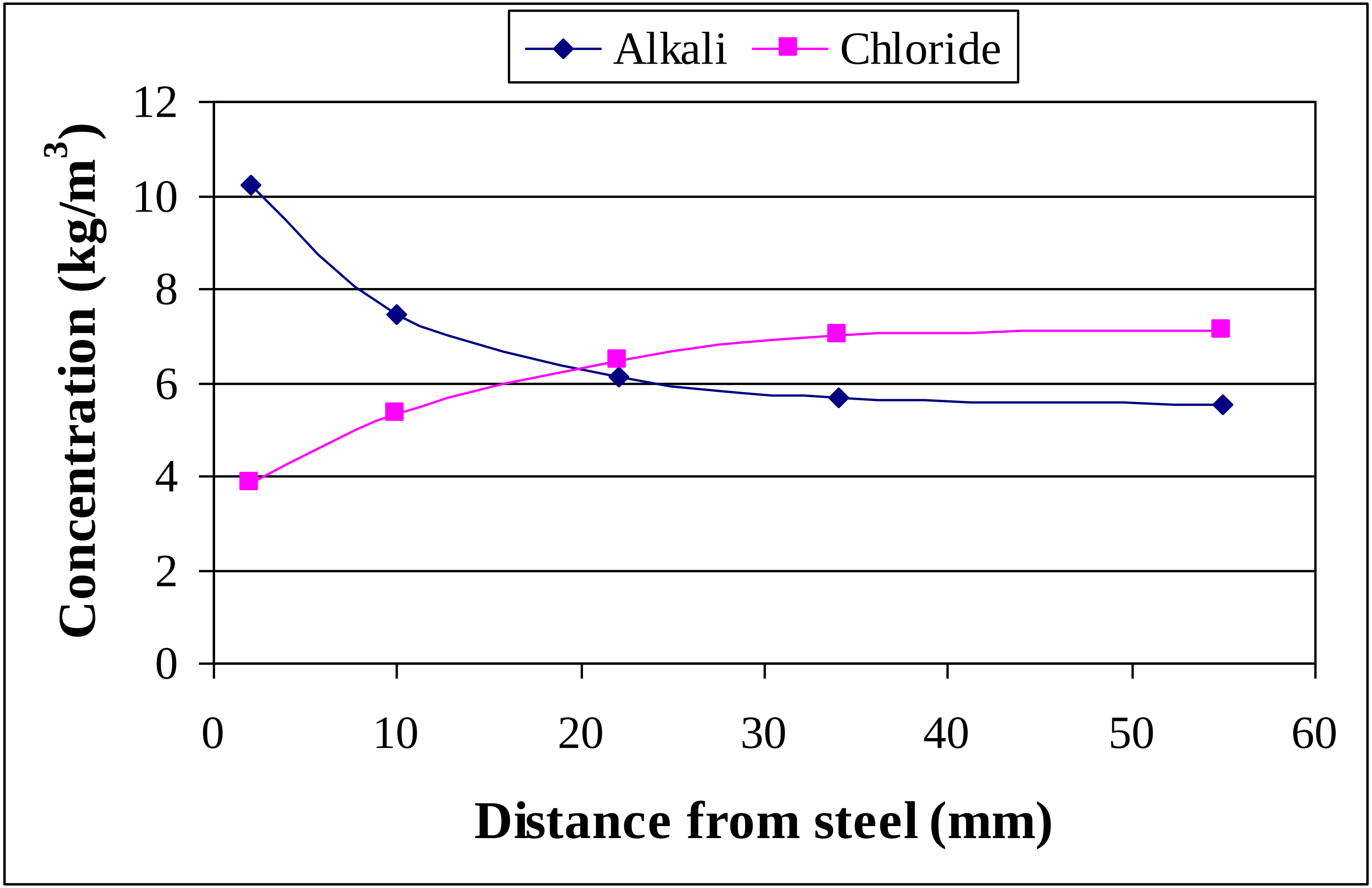
- This leads to reduced $[Cl^-]/[OH^-]$ ratio and a reduced corrosion risk

Effects of Steel Polarisation



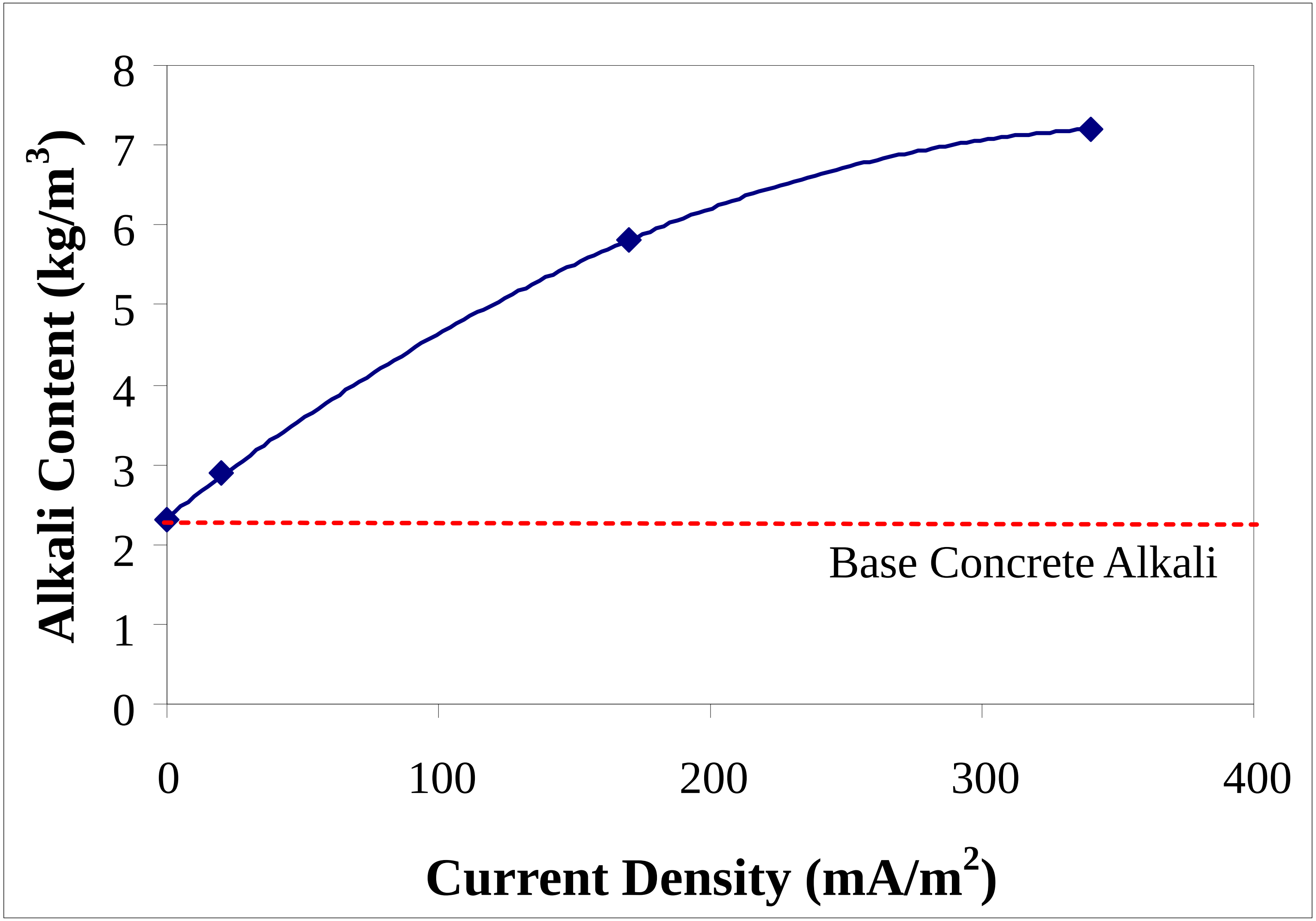
Polarisation of steel

Effects of Steel Polarisation



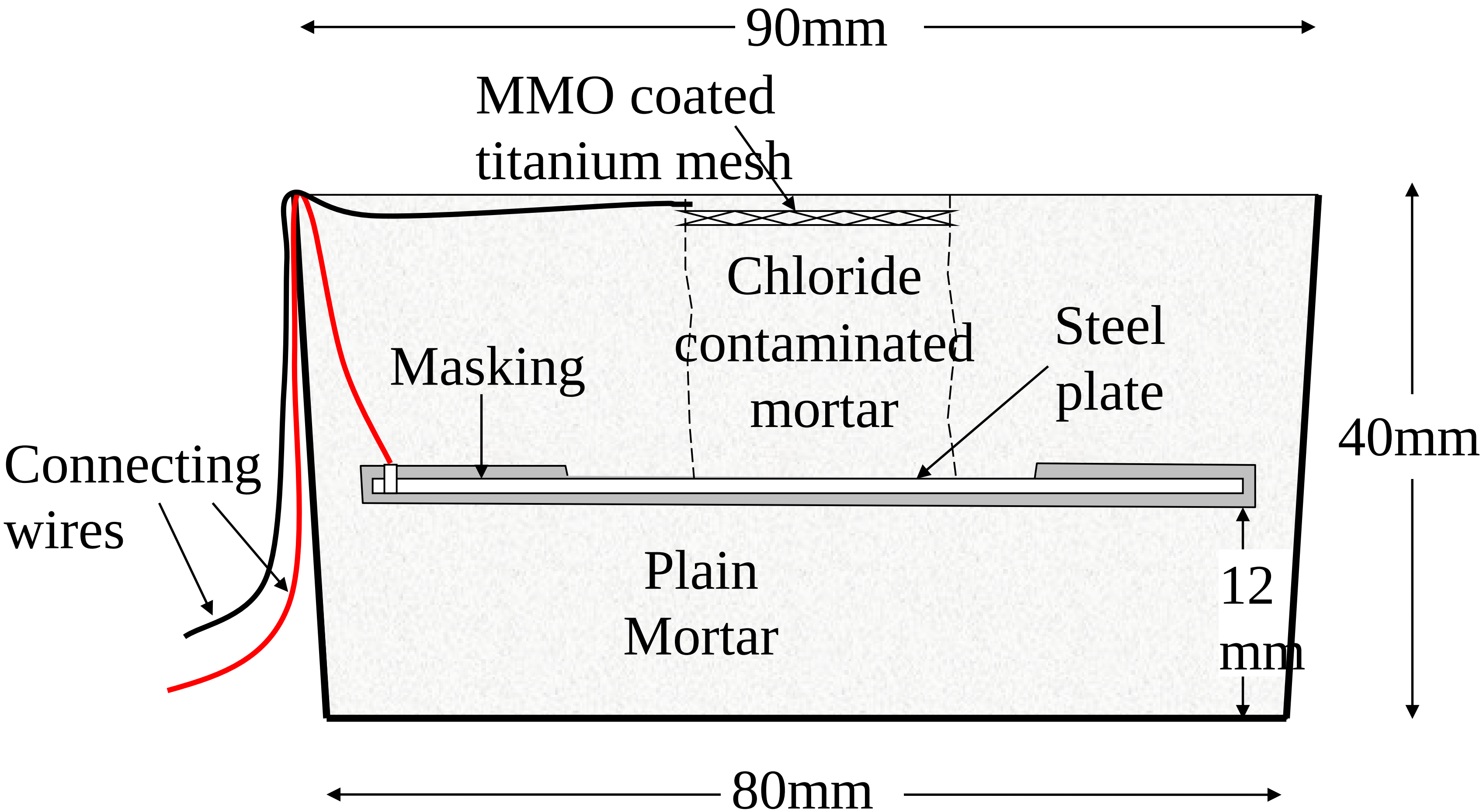
Polarisation of steel

Effects of Steel Polarisation



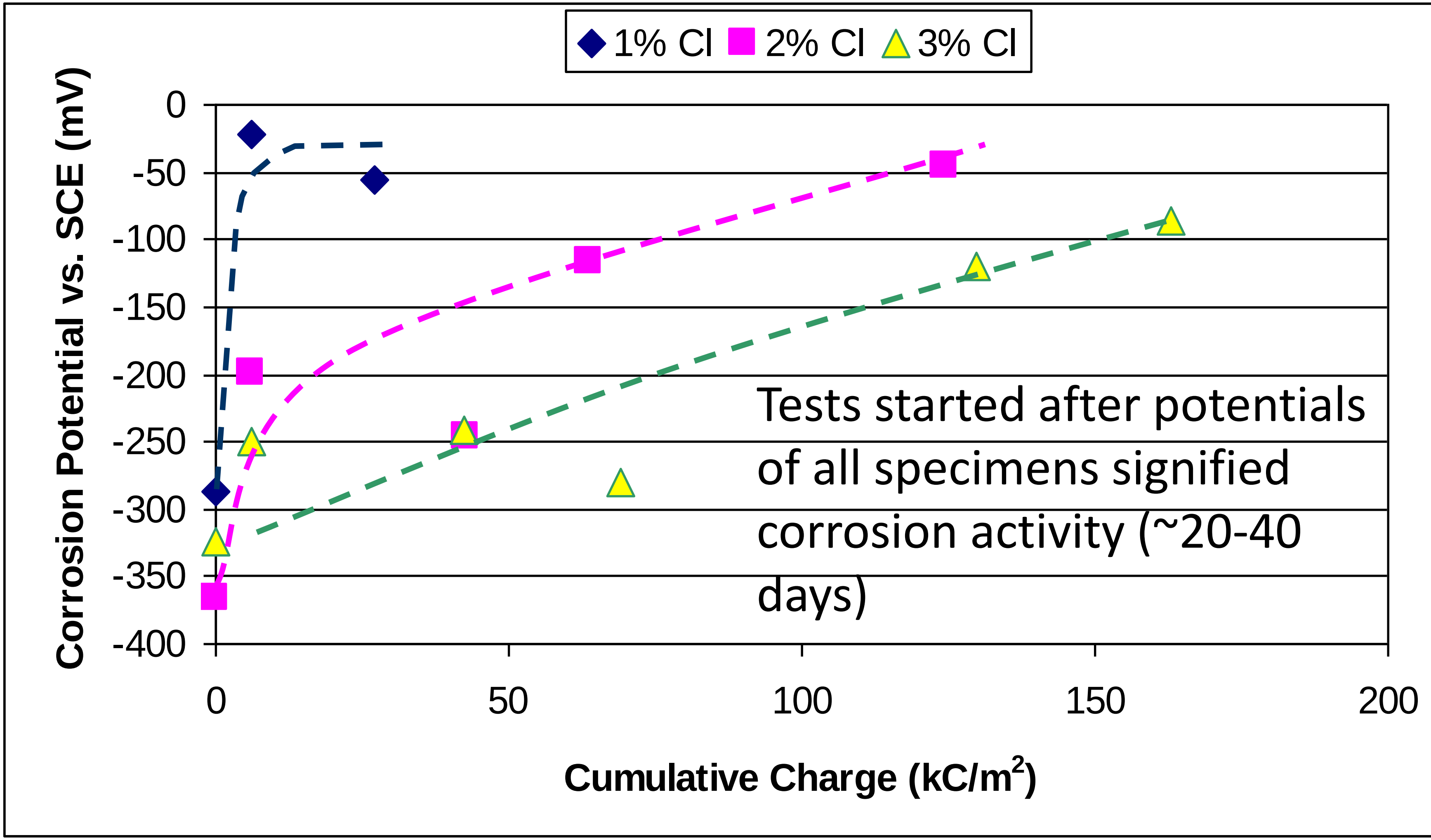
Polarisation of steel

Testing in the Lab



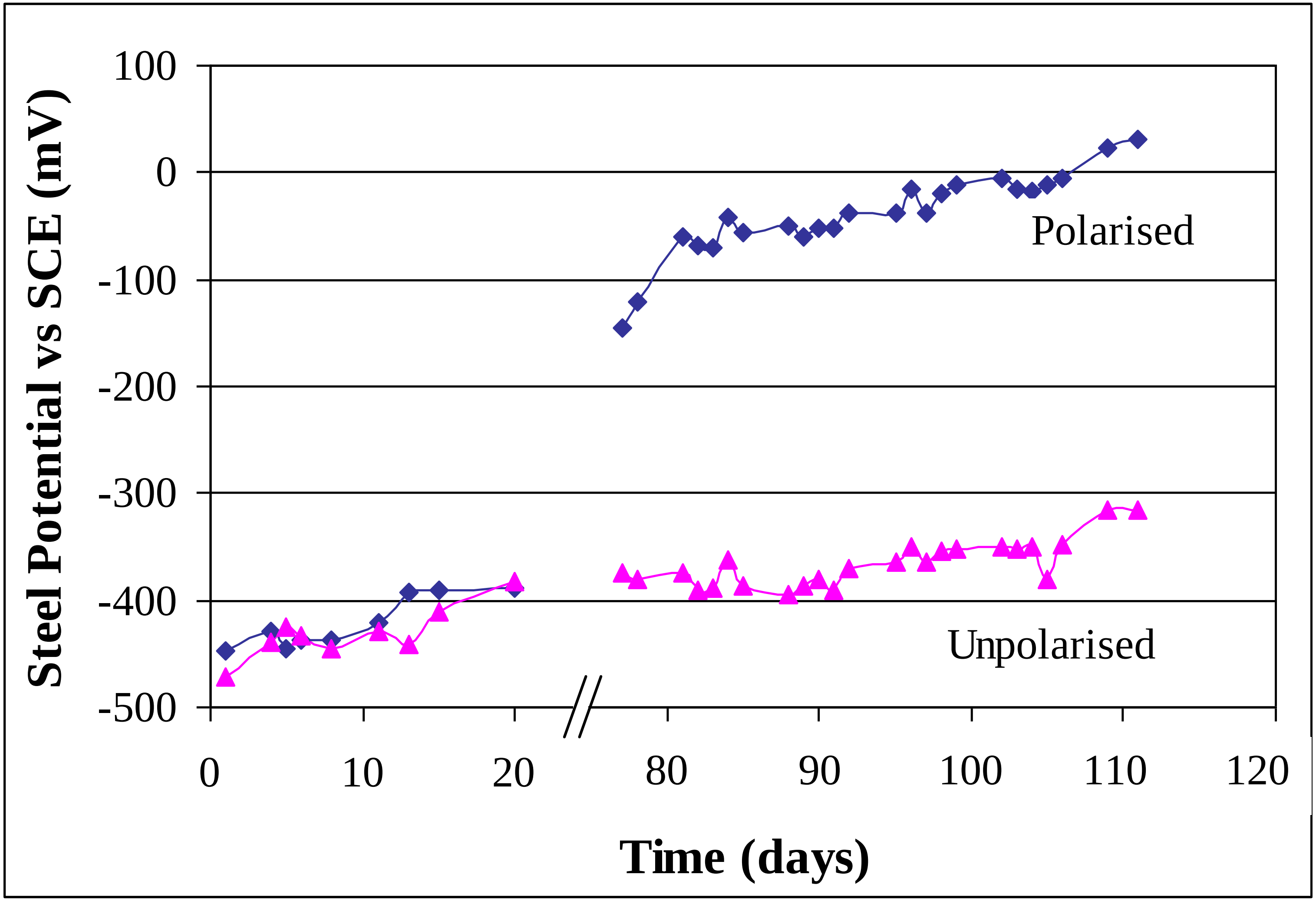
Small mortar specimens for tests

Testing in the Lab



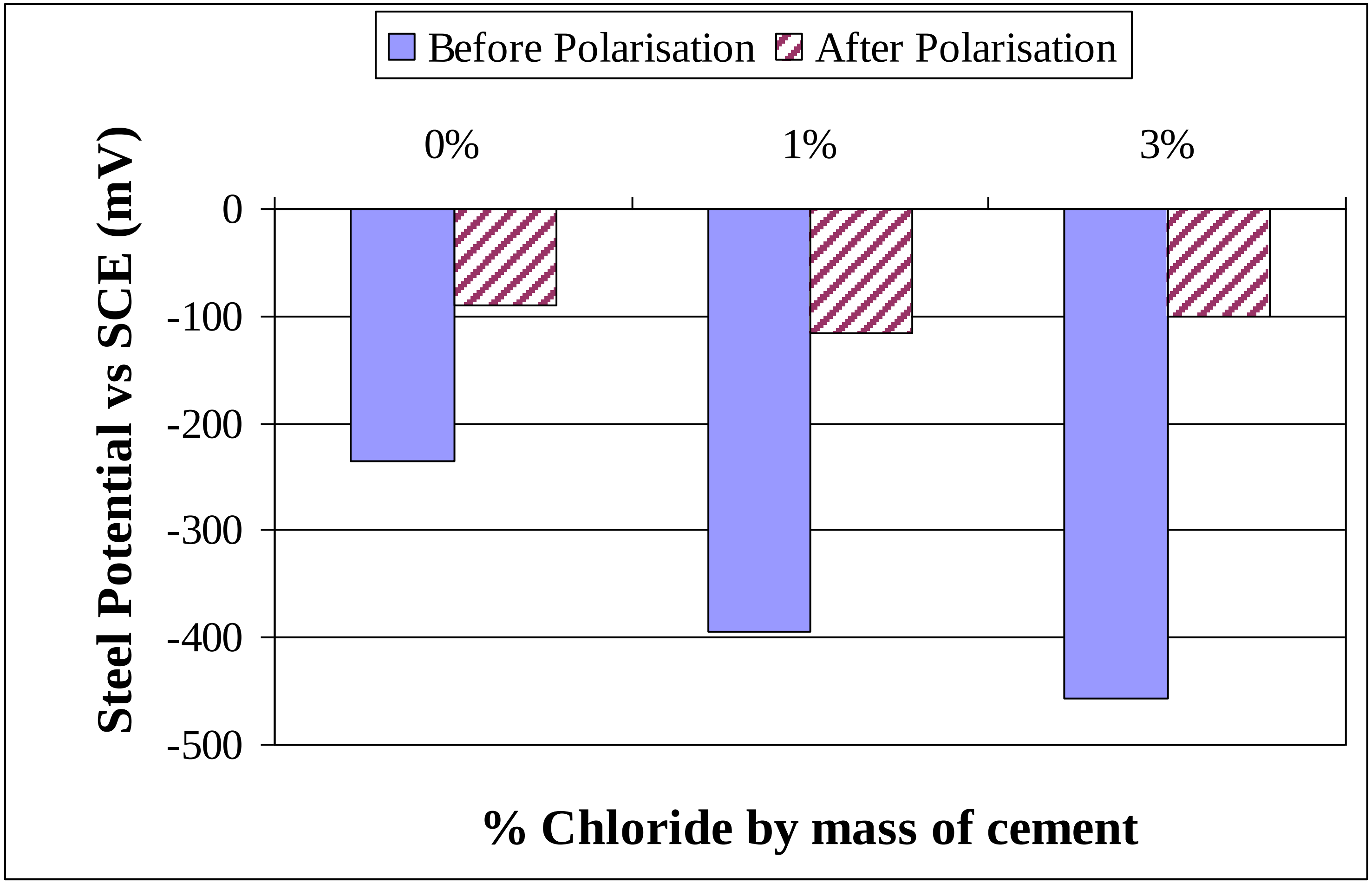
Effect of charge on steel potential at various chloride additions to the mortar (c.d. = 30 mA/m^2)

Testing in the Lab



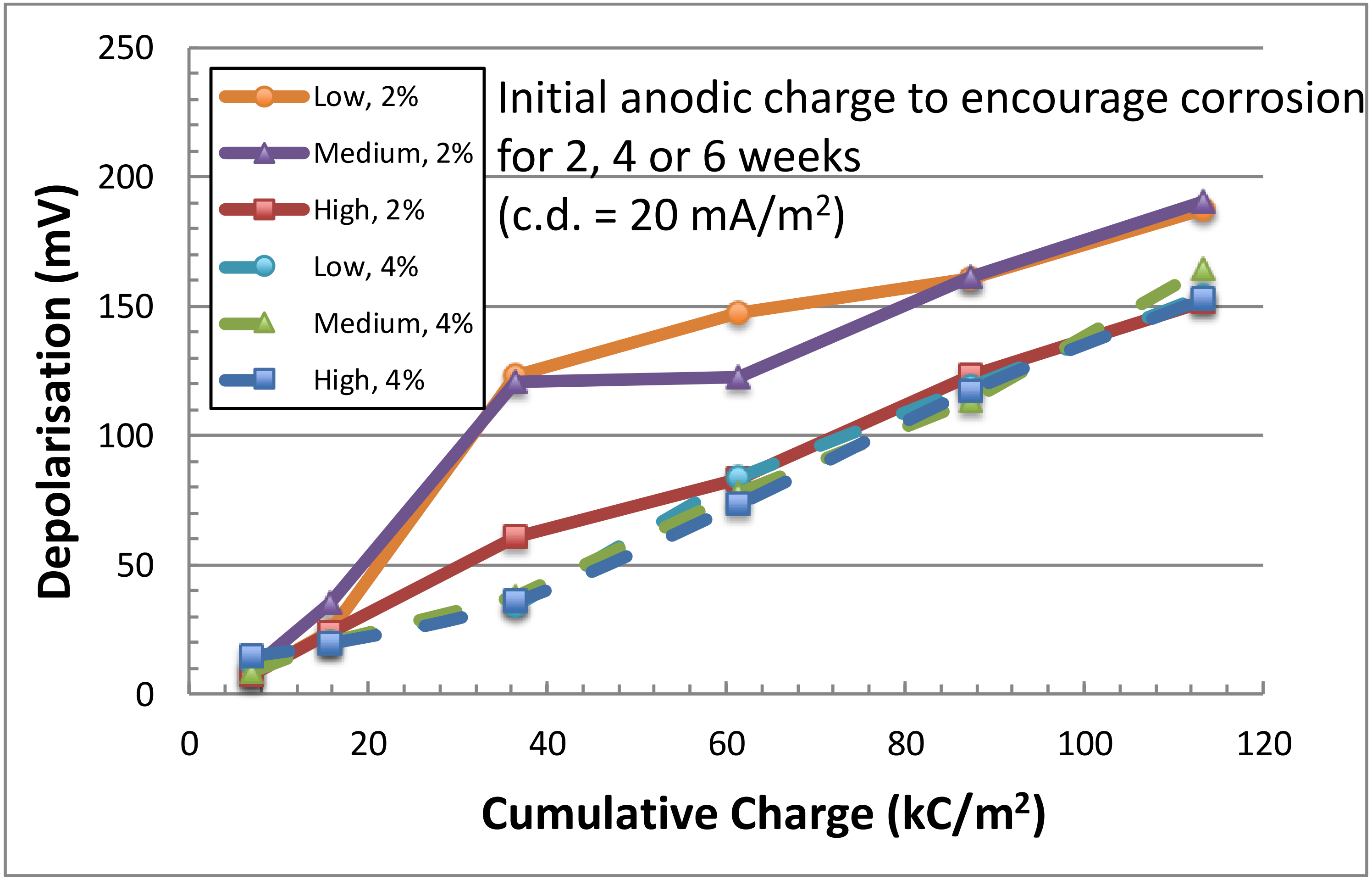
Polarised steel in 3% chloride vs unpolarised control

Testing in the Lab



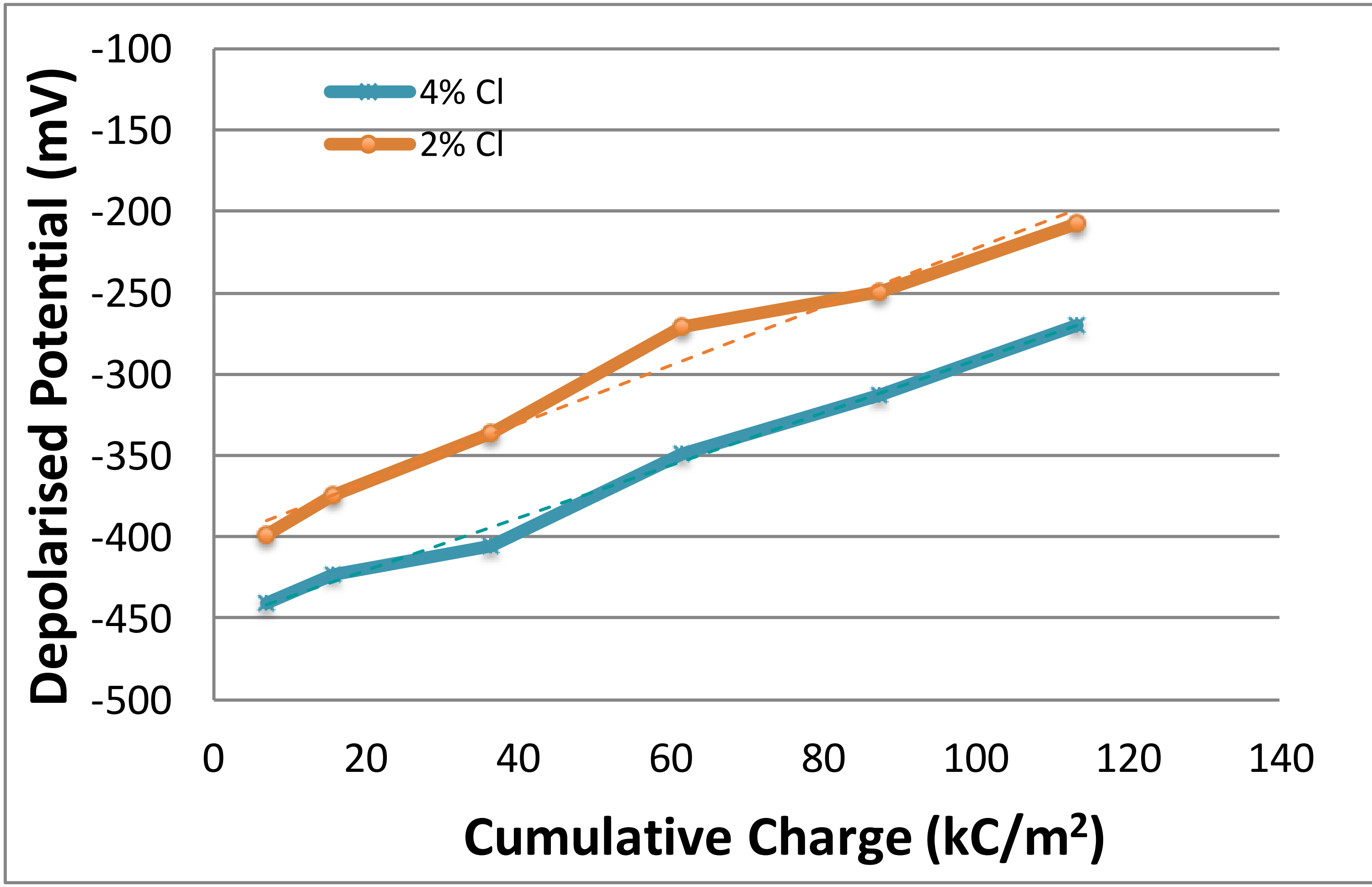
Polarised steel before and after cathodic charge of $150kC/m^2$ (c.d. = $40mA/m^2$)

Testing in the Lab



Level of Depolarisation with Increasing Cumulative Charge (c.d. = 50 mA/m^2)

Testing in the Lab



Depolarised Potentials with Increasing Cumulative Charge (c.d. = 50 mA/m²)

Testing in the Lab

	50 mA/m^2		30 mA/m^2	
	2% Cl	4% Cl	2% Cl	3% Cl
Charge require to passivate steel (kC/m^2)	65	110	120	190

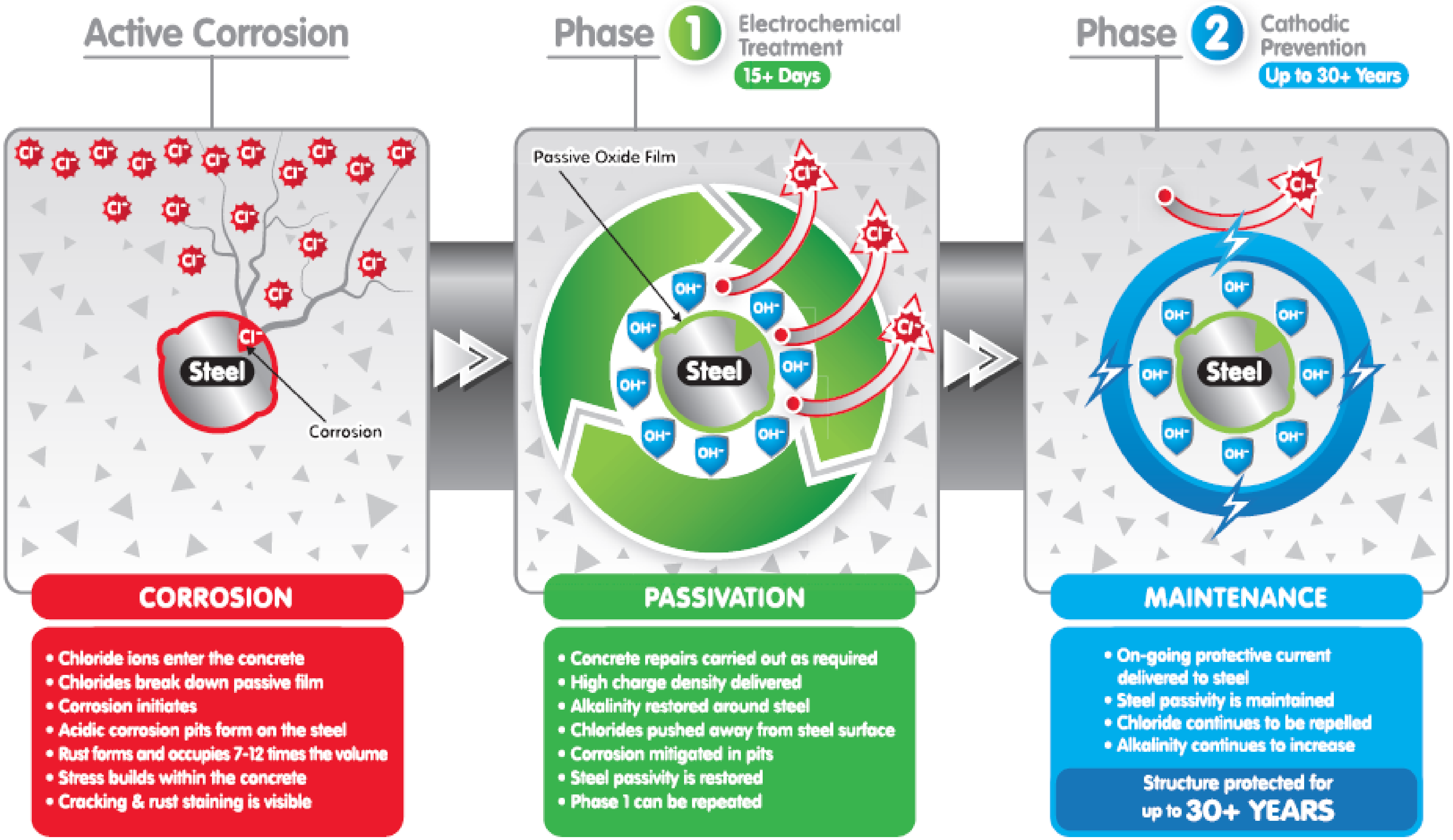
Charge required to arrest corrosion in relation to current density

Two-Stage Process

A Two-Stage Process is feasible to control reinforcement corrosion

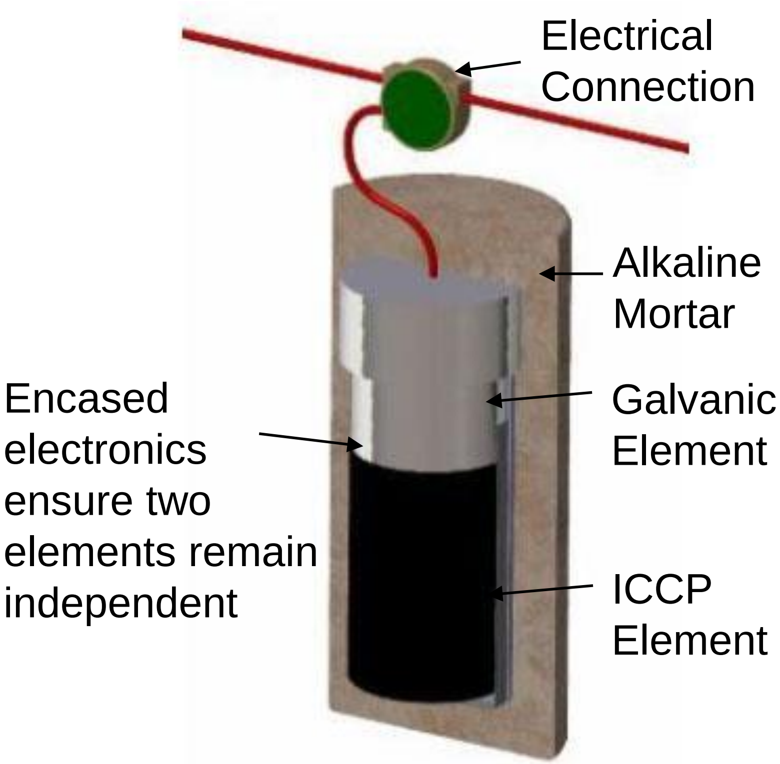
- Stage-1, Arrest Corrosion and achieve passivity of the steel by applying an adequate initial charge
- Stage-2, Continue to maintain the passive state of the steel long-term with a small ‘cathodic prevention’ current

Two-Stage Process



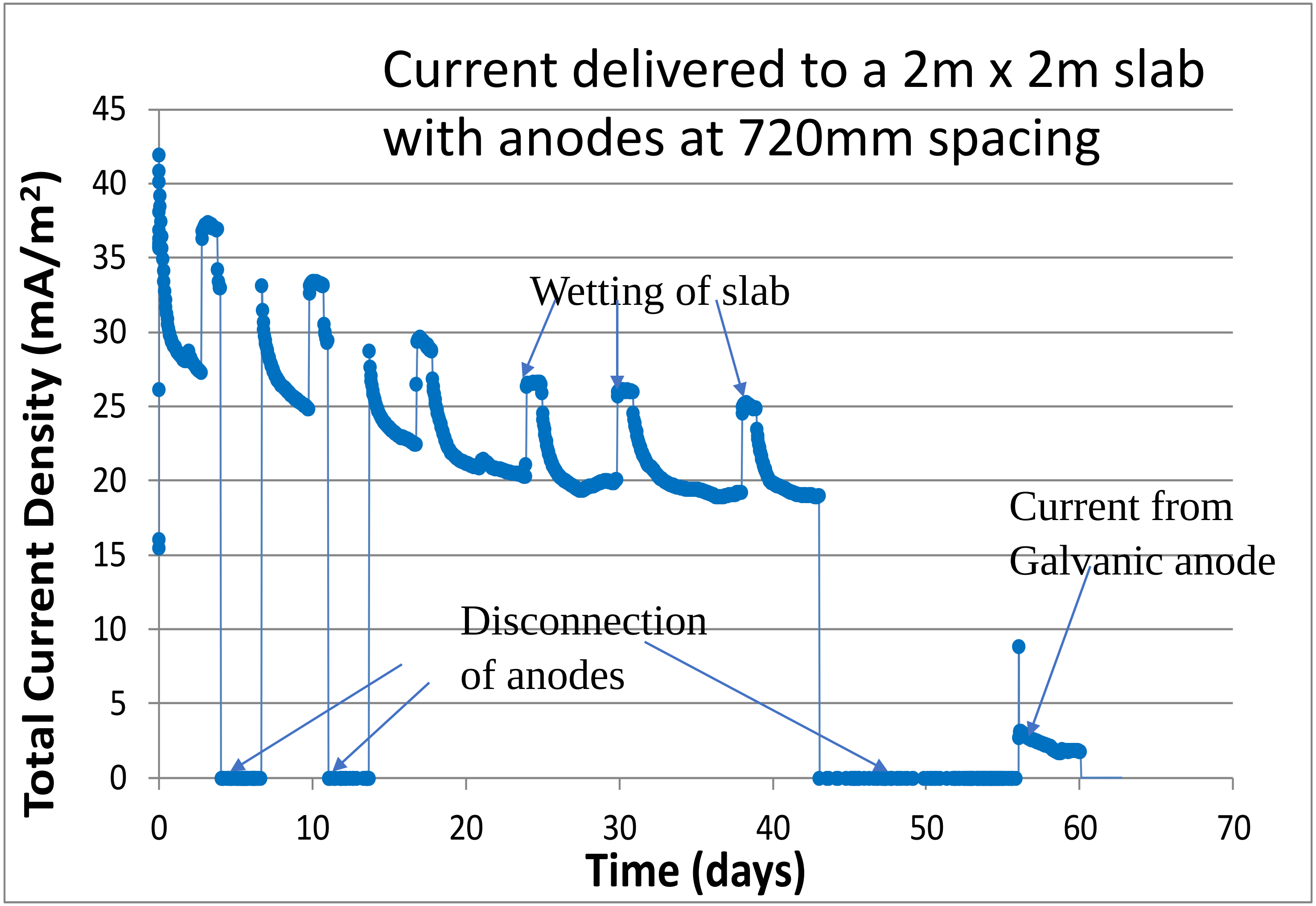
Diagrammatic representation of the Two-Stage Process

Fusion™ Anodes on Site



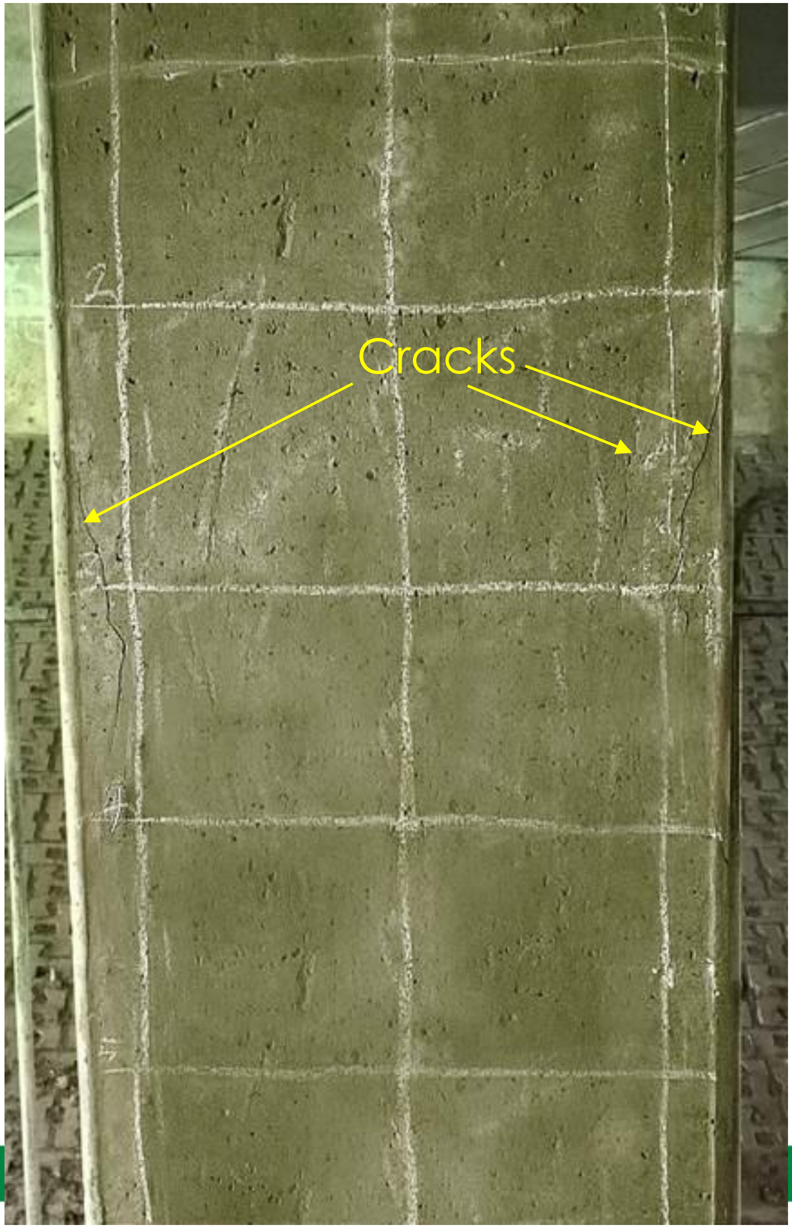
- ICCP element comes with various voltage and total charge capabilities
- Choice of anode and spacing allows a design current density and total charge delivery

Two-Stage Process



Current density first by the ICCP component and secondly from the galvanic anode

Fusion™ Anodes on Site



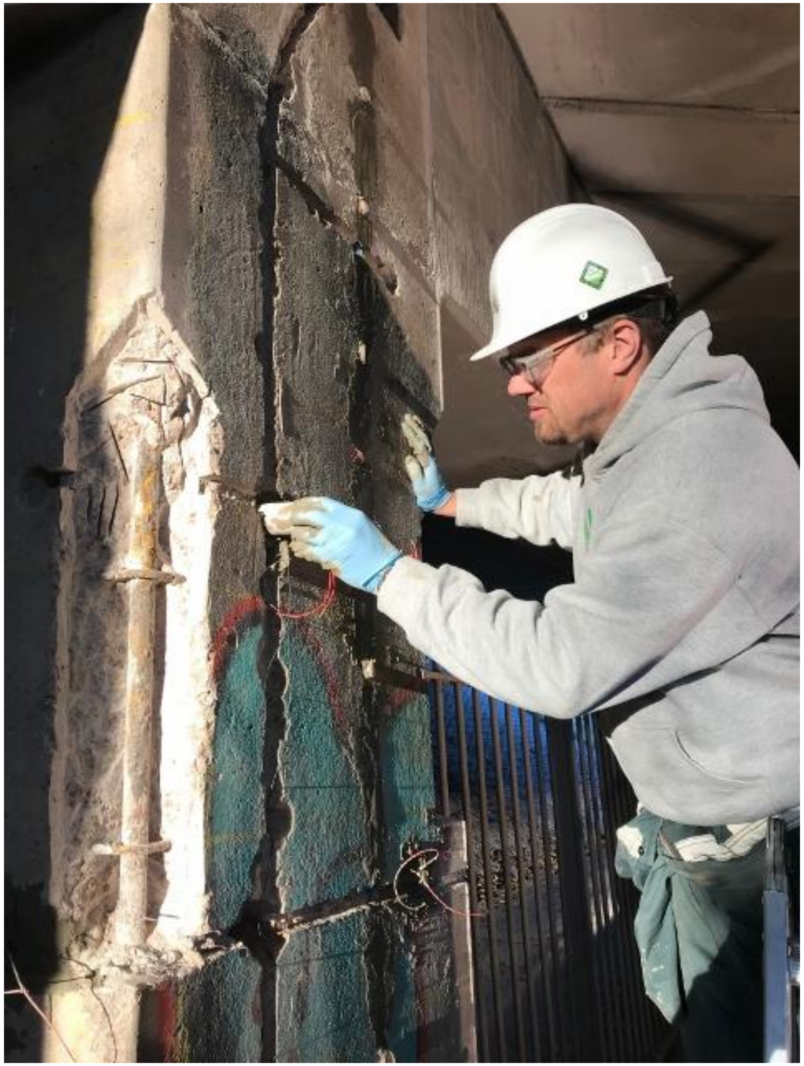
Cracks in column caused by reinforcement corrosion

Range of Chloride Concentration in 11 test locations,

0.5 – 2.05 % by weight of cement

Mean = 1.27%

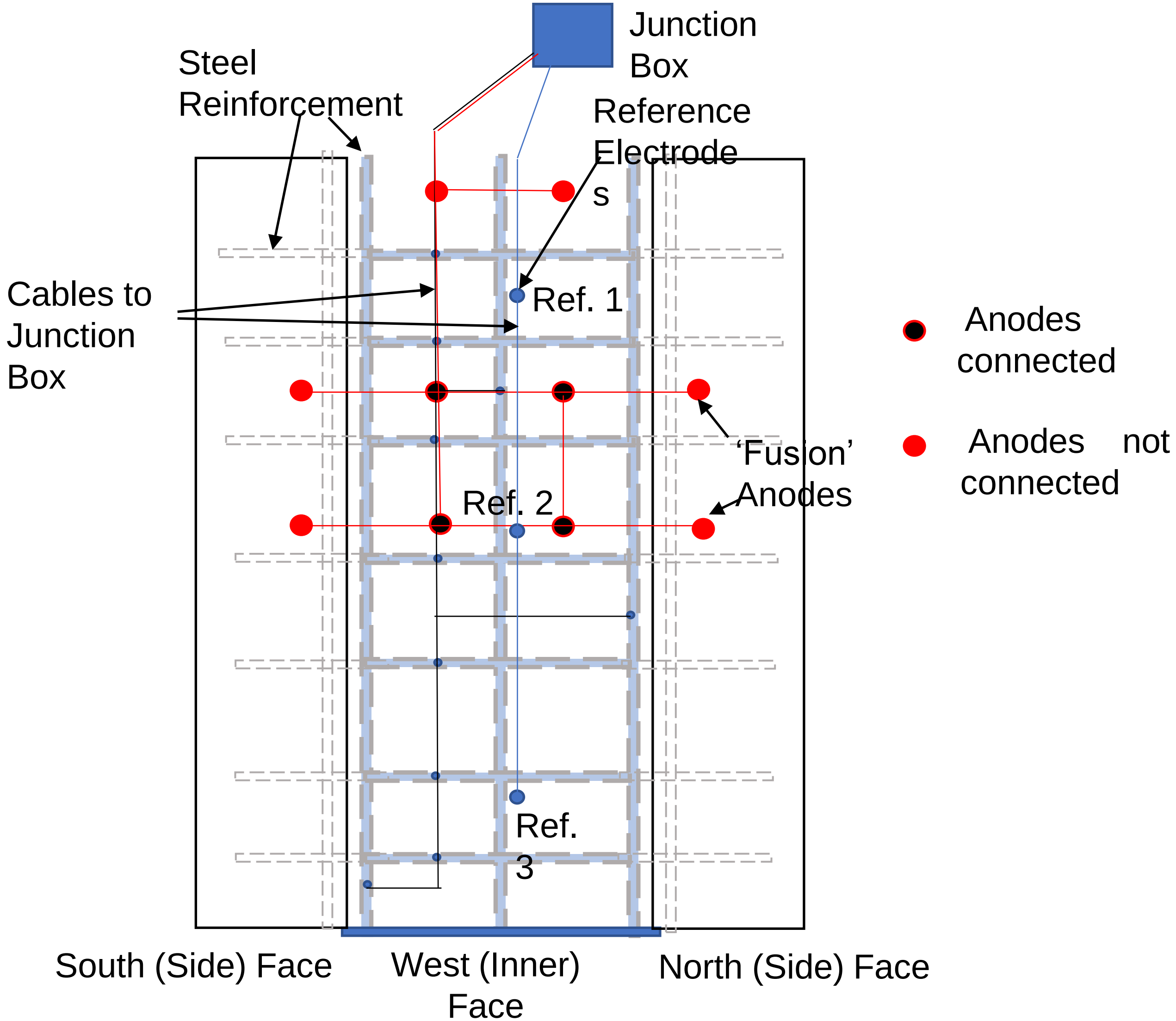
Fusion™ Anodes on Site



Installation of Fusion™ Anode

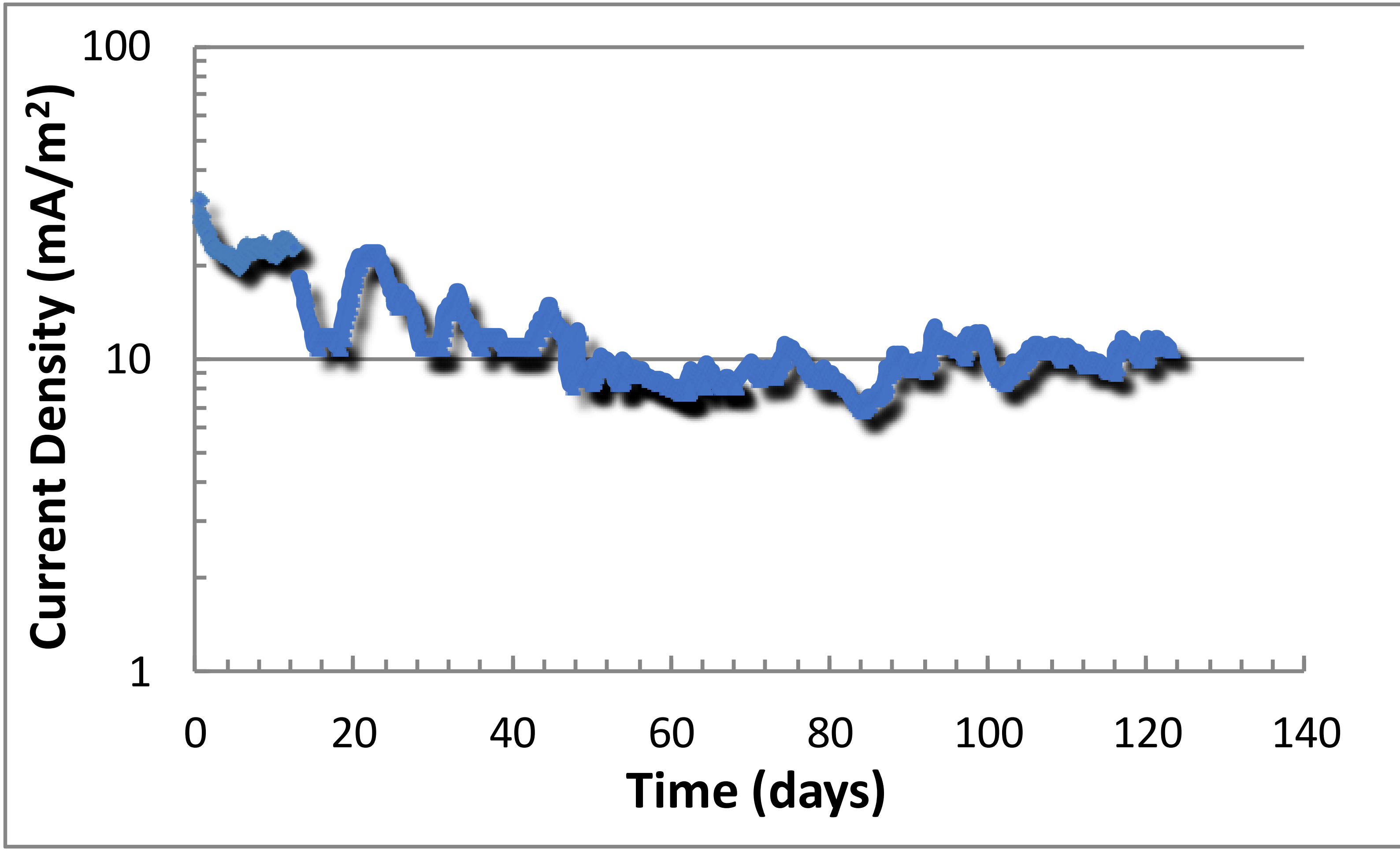
Installed Fusion™ Anode

Fusion™ Anodes on Site



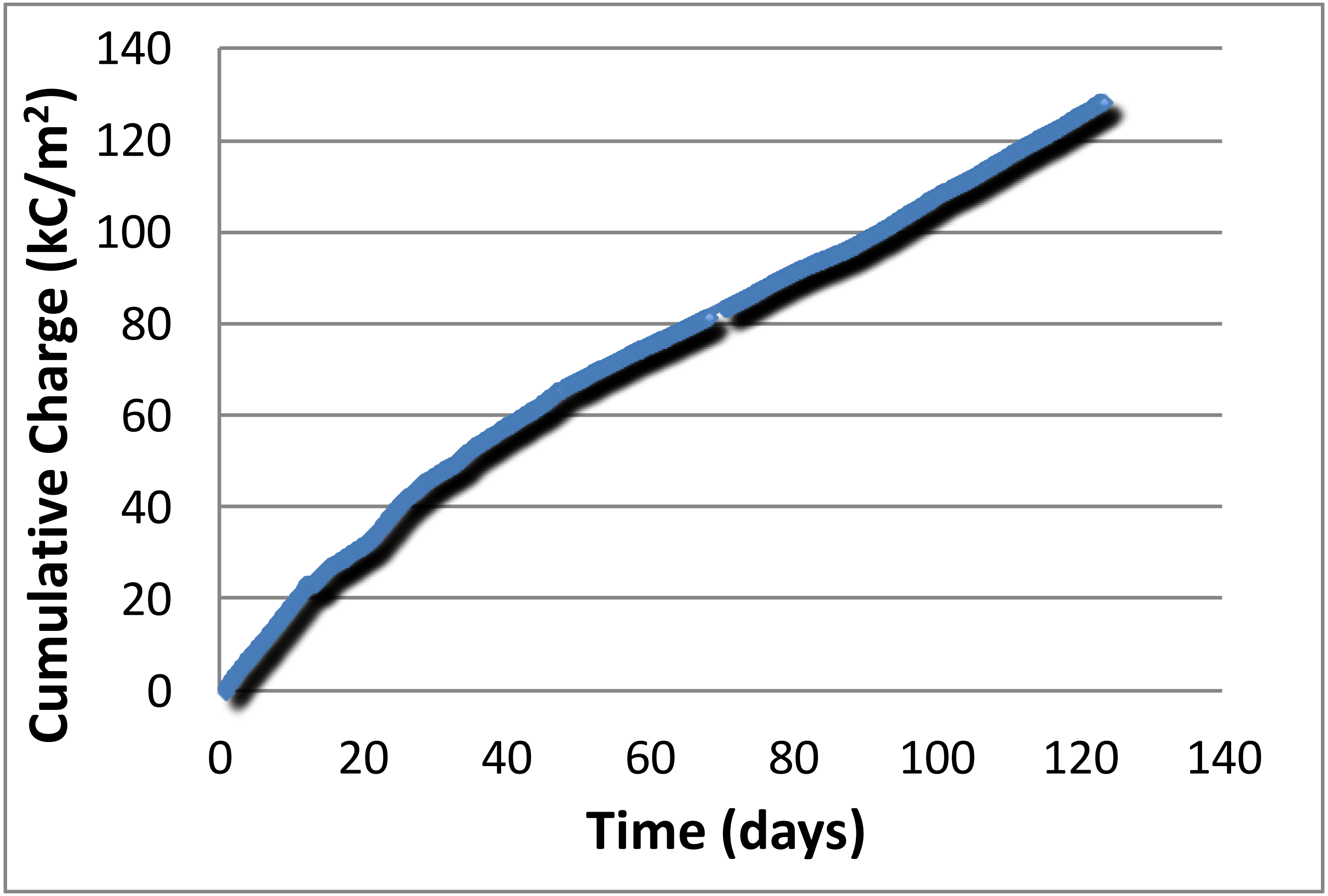
Position of anodes, reference electrodes and steel connections (Set-1 anodes)

Fusion™ Anodes on Site



Variation of current density with time

Fusion™ Anodes on Site



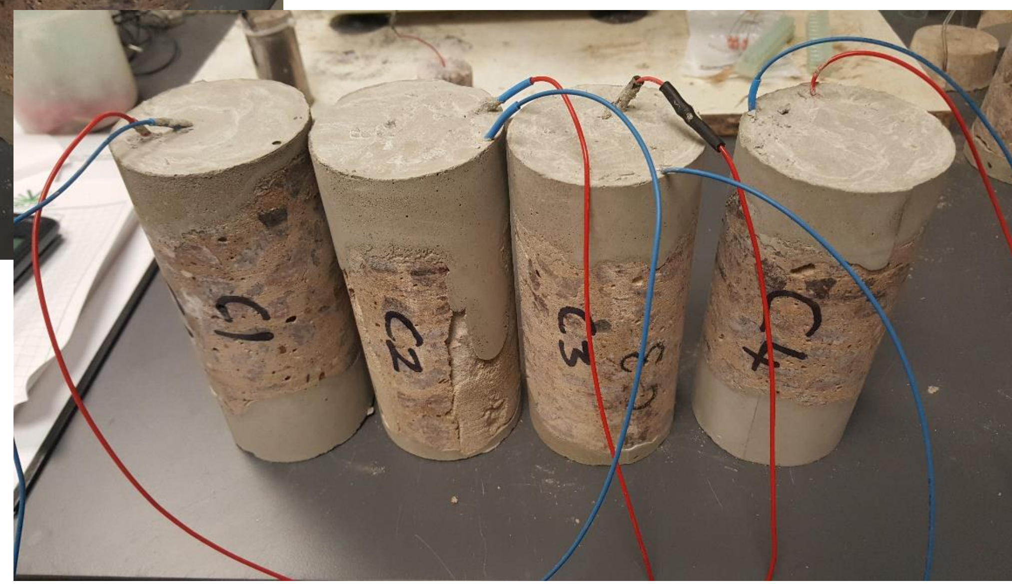
Mean cumulative charge delivery to the steel with time of polarisation

Fusion™ Anodes from Site

All anodes removed after 125 days for lab testing

As Cored from site

Edge repaired with mortar



Cored Set-1 Fusion Anodes from Leicester

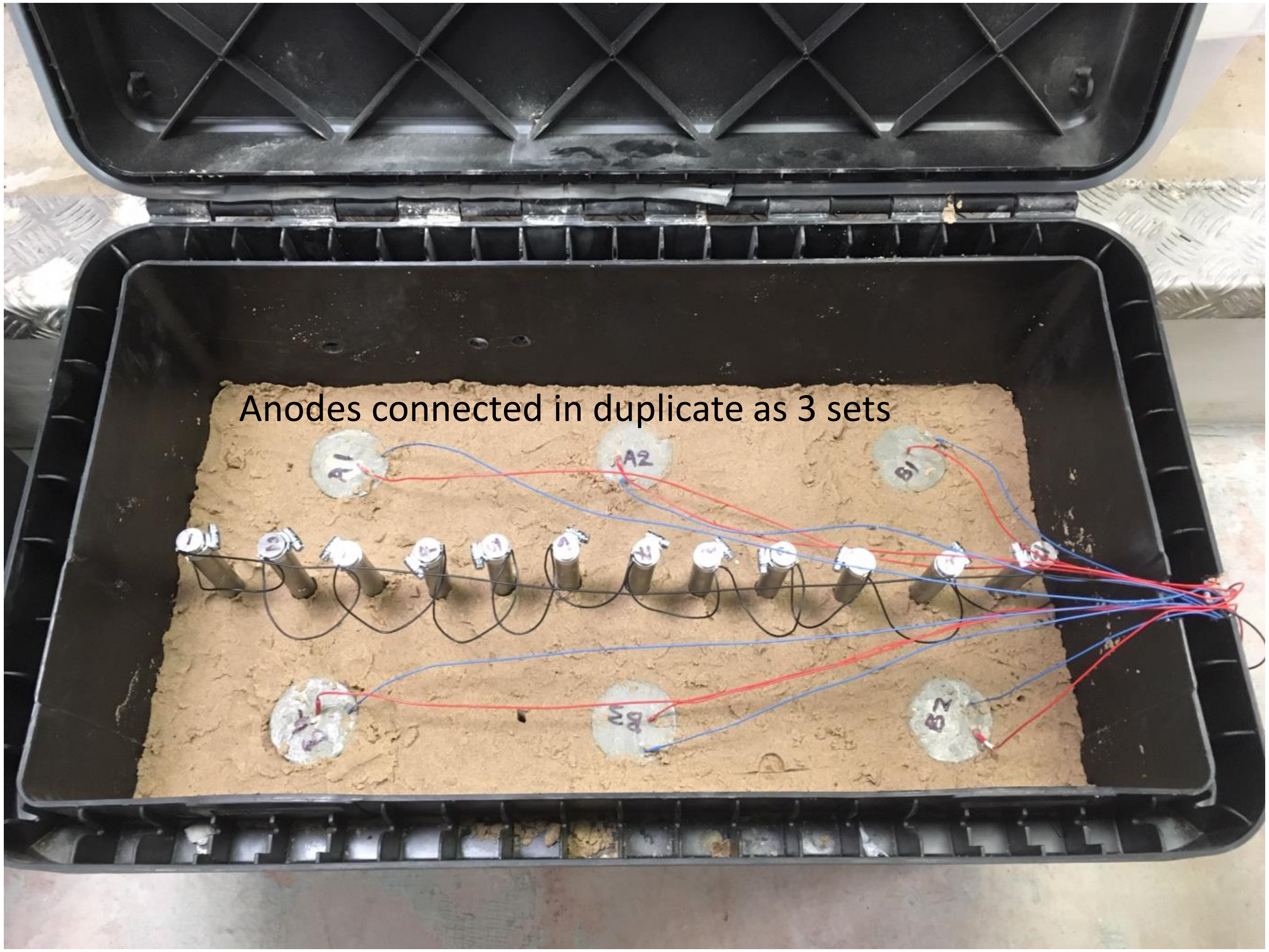
Fusion™ Anodes from Site

ICCP mortar element removed and analysed for LiOH content

No corrosion on stainless steel current carrier

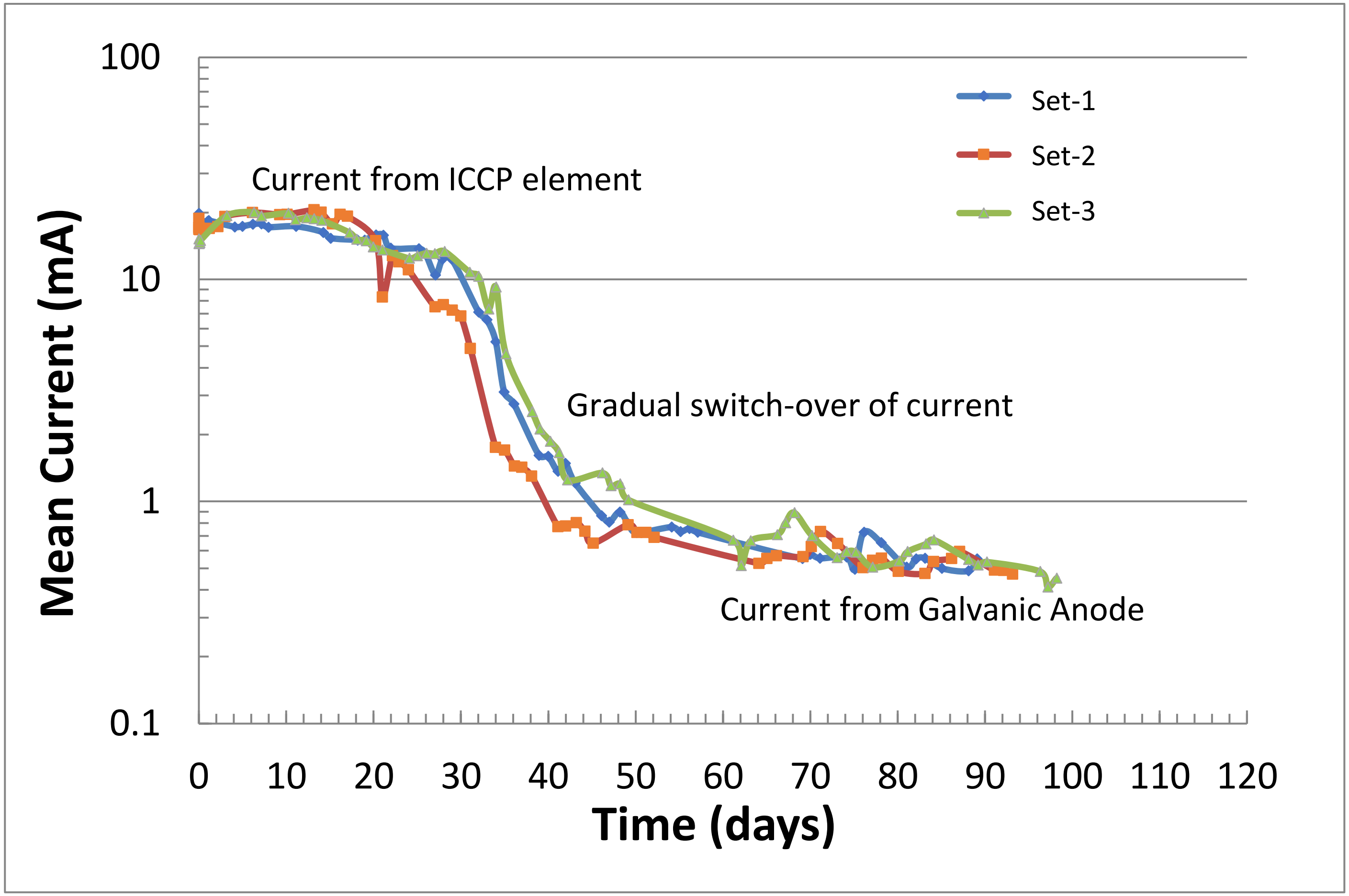
Cored Anode used at Leicester

Fusion™ Anodes in Lab



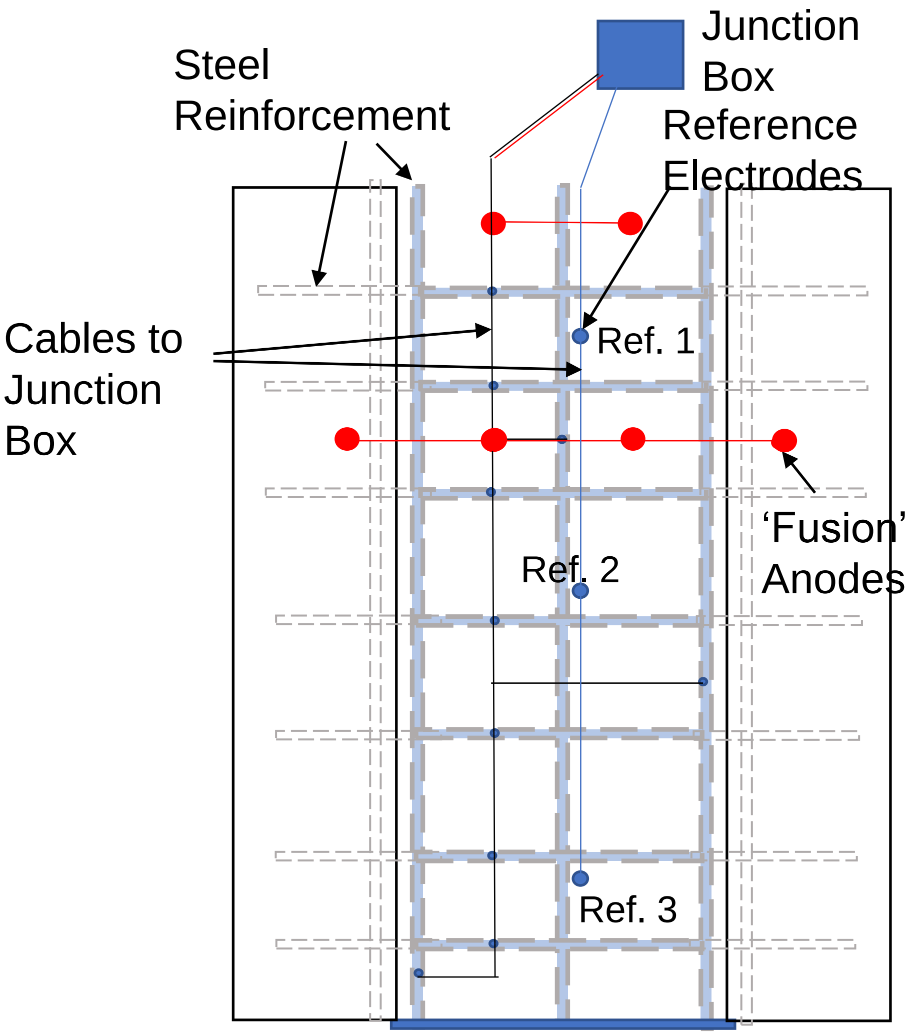
Sand-box layout of six out of eight anodes

Fusion™ Anodes in Lab



Mean current output per anode per set of two

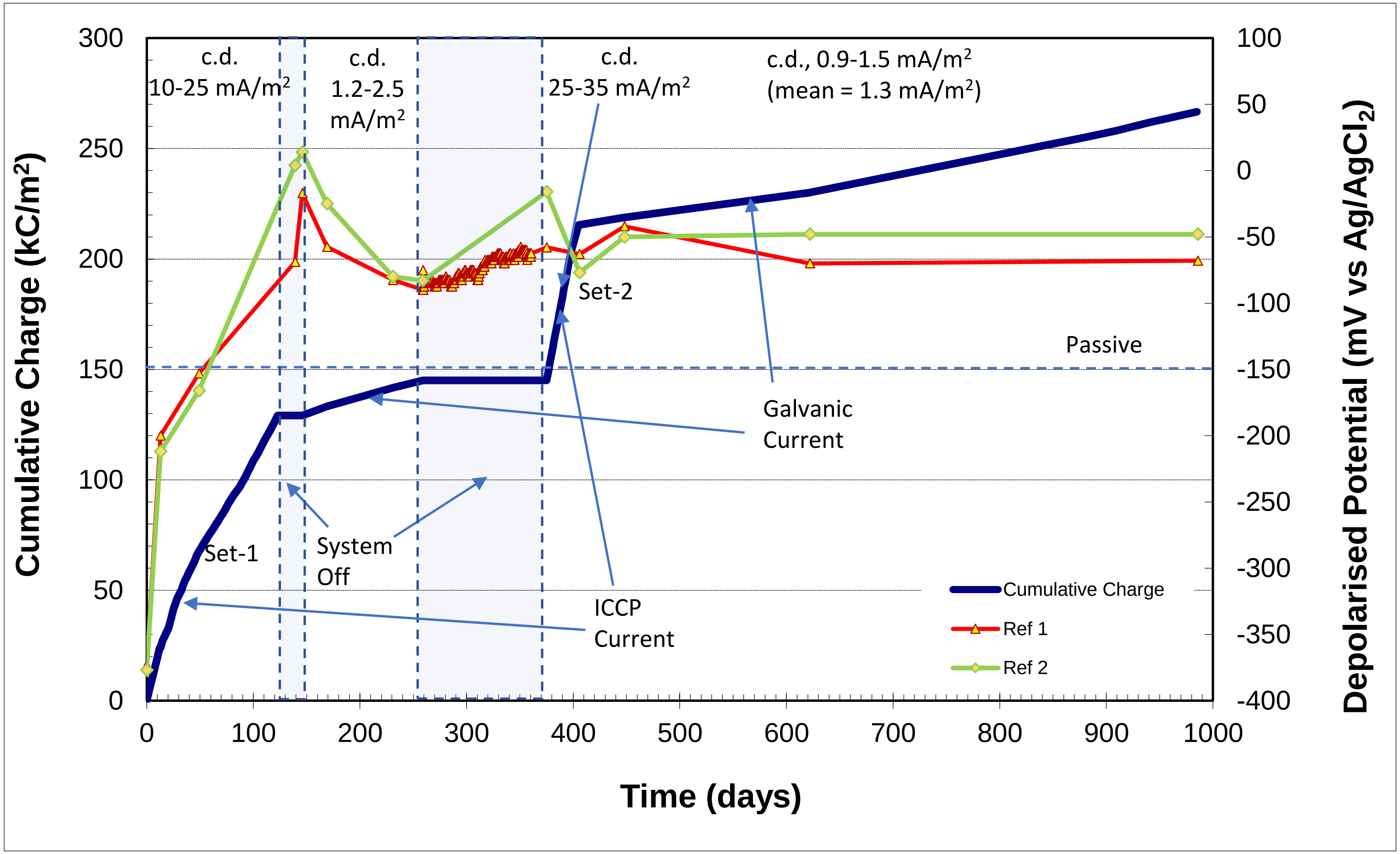
Fusion™ Anodes on Site



Six new lower charge capacity anodes replaced removed anodes

Position of anodes, reference electrodes and steel connections (Set-2 anodes)

Fusion™ Anodes on Site



Charge Delivery and Depolarised Potentials with Time

Fusion™ Anode

Conclusions

- An initial charge at the top end of CP current densities can arrest corrosion of steel
- Level of applied charge to achieve corrosion arrest depends on the corrosivity of the concrete environment and the level of applied current density
- Passivation of steel can be maintained long-term with galvanic anodes
- A Two-Stage CP process is thus achievable with the use of specially designed modular Fusion™ anodes

Thank you for your attention