Cathodic Protection of Highway Structures

ACPM
ADVANCED CORROSION PROTECTION MATERIALS

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1

Overview

- The Problem
- Corrosion of steel in concrete
- Repair Options
- Cathodic Protection
- Example Projects

2

Winter Treatment

- Current practice
  - Application of de-icing salts keeps our roads safe
- Unwanted effects
  - Increased corrosion of reinforced concrete structures

3

Winter Treatment - Indicative Cost Comparison

•Bulk cost of de-icers commonly used in the UK (Sourced Halcrow 2012)

- Dry Salt (Sodium Chloride) - £25 / tonne
- Treated Salt (ABPs) - £32 / tonne
- Pre-wet Salt - £25 to £35 / tonne
- Acetates - £600 / tonne
- Urea - £650 / tonne
- Glycol - £1000 / tonne

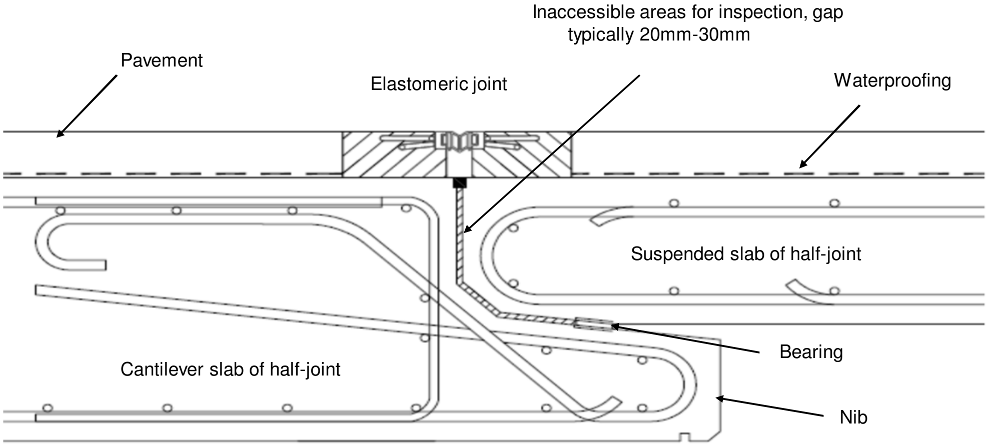
4

Inspection and Repair - Issues

- Accessibility for inspection and repair are limited
- Conventional repair options are not viable without shutting the motorway
- Regular patch repairs are impossible and are not sustainable

5

Access for Inspection and Repair



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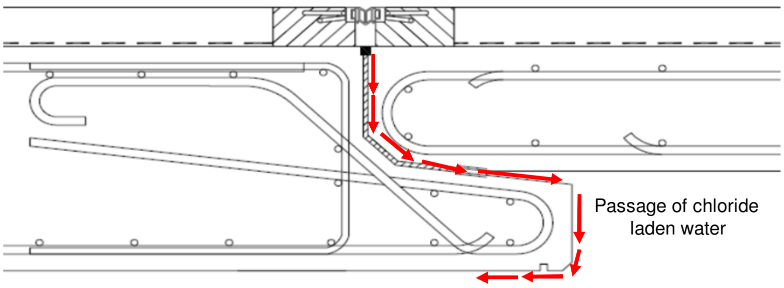
Deterioration to Half-Joints and bearing shelves

- Carriageways are contaminated with chloride ions due to de-icing salts
- Chloride laden water leaks through defective joints



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Leaking Joints

- The use of chloride based de-icing salts are expected to continue
- Joints leak and can be expected to continue to leak in the future

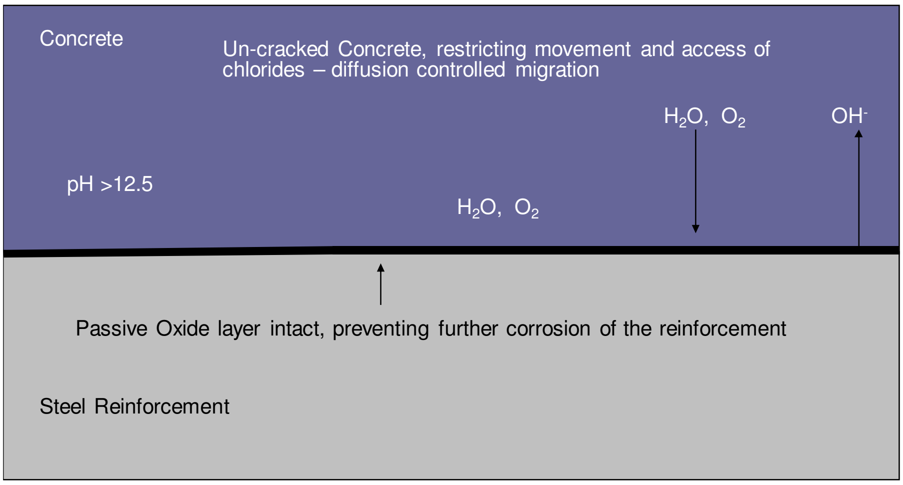
8

Corrosion of Steel in Concrete

- Steel in uncontaminated concrete is normally protected against corrosion
- Cement hydration produces large quantities of calcium, sodium and potassium hydroxides which leads to high pH
- pH 12.5 to 13.5, promotes the formation passive oxide layers which prevent further corrosion

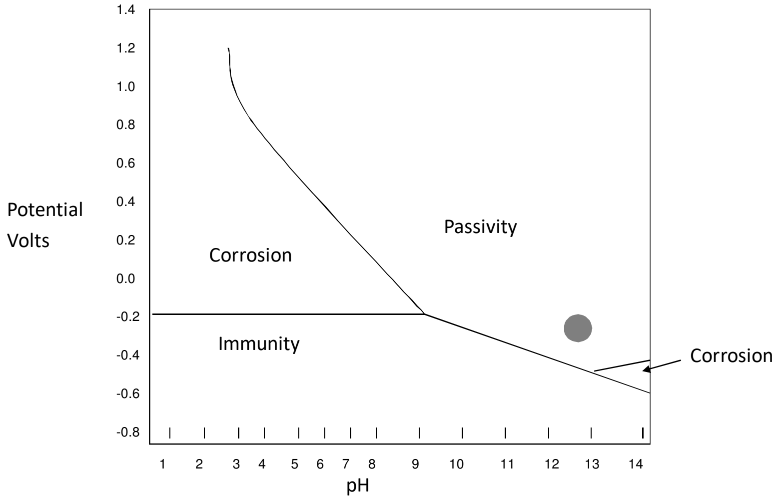
9

Steel in Uncontaminated Concrete



10

Potential – pH diagram for Iron in Water



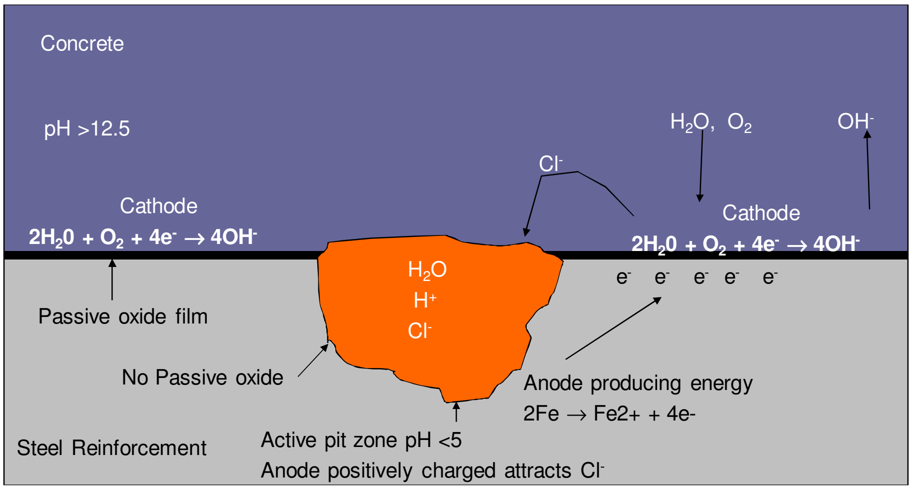
11

Chloride Corrosion of Steel in Concrete

- Chloride contamination leads to a loss of the protective oxide layers
- Once a critical chloride level occurs at the steel surface, corrosion initiates
- Very localized pitting corrosion and section loss is typical for chloride contaminated concrete

12

Chloride Induced Pitting Corrosion of Steel in Concrete



13

Chloride Induced Pitting Corrosion of Steel in Concrete

- Presence of chloride ions leads to localised ‘pitting’ corrosion
- Significant section loss of rebar is common, impacting tensile capacity

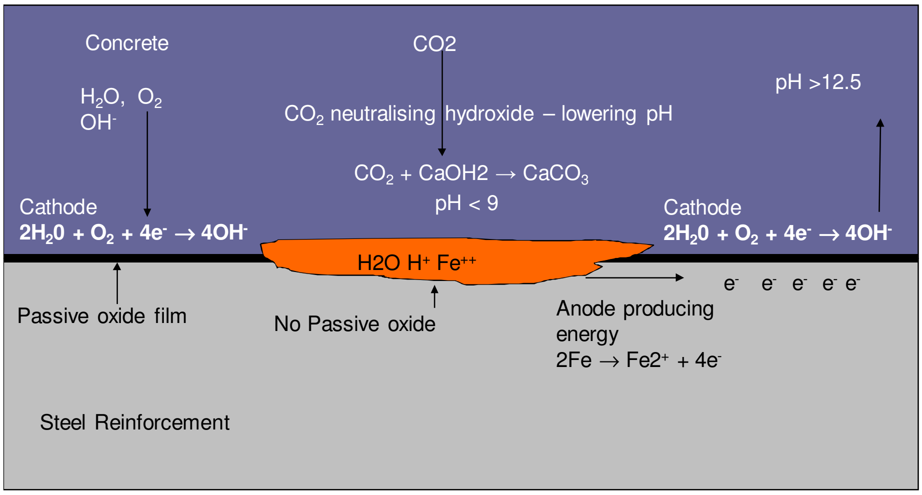
14

Carbonation Induced Corrosion of Steel in Concrete

- The passive films rely entirely on the pH
- Any drop in the pH will lead to breakdown of the passive film and the initiation of corrosion
- Carbon dioxide from the atmosphere can react with the free OH^- within the concrete lowering the pH of the pore water
- General corrosion occurs leading to uniform loss of metal, typical of general atmospheric corrosion

15

Carbonation Induced Corrosion



16

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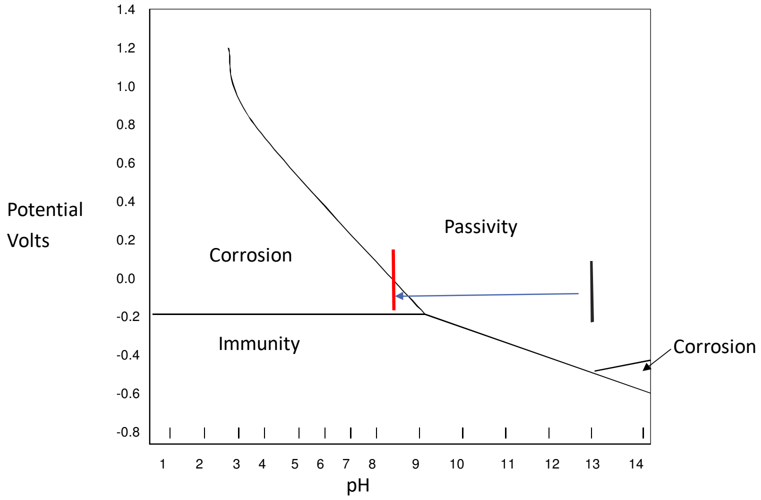
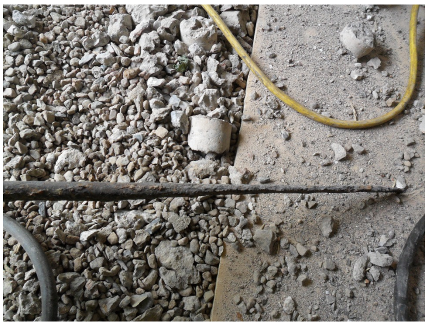


17

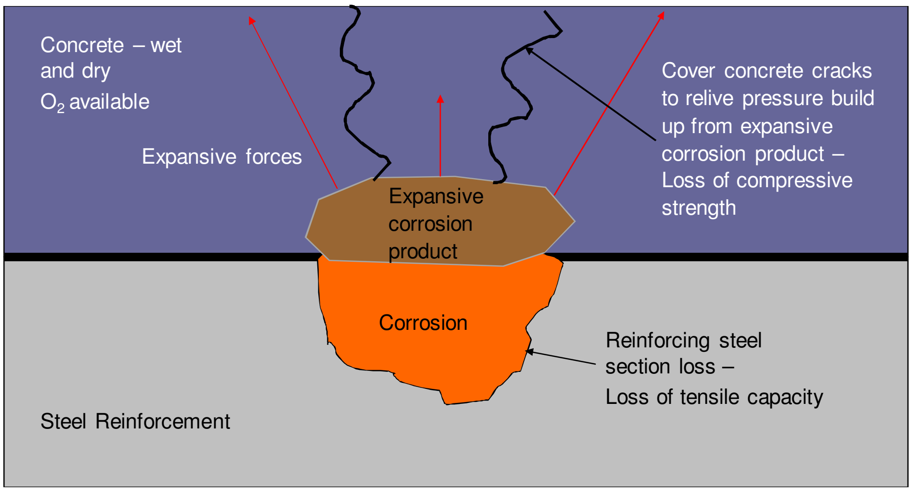
Carbonation Induced Corrosion of Steel in Concrete

- Loss of pH leads to general corrosion
- Section loss in extreme cases is tapered, due to general section loss following loss of protective concrete cover



18

Impact of Corrosion of Steel in Concrete with O_2



19

Deterioration to Half-Joints

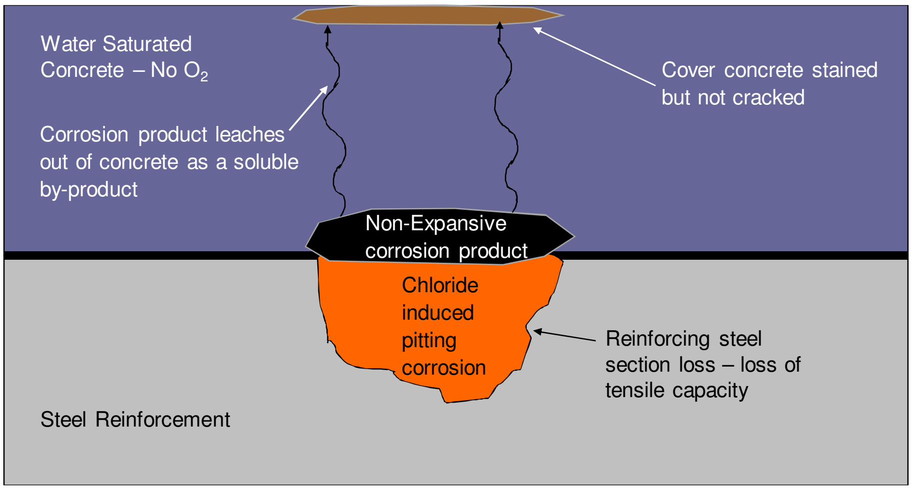
- Corrosion products creates an internal pressure in the cover concrete
- Leads to cracking, delamination and spalling of cover concrete
- Exponential increase in corrosion and concrete deterioration due to cracked concrete

20

Impact of Corrosion of Steel in Concrete

21

Impact of Corrosion of Steel in Concrete - No O_2



22

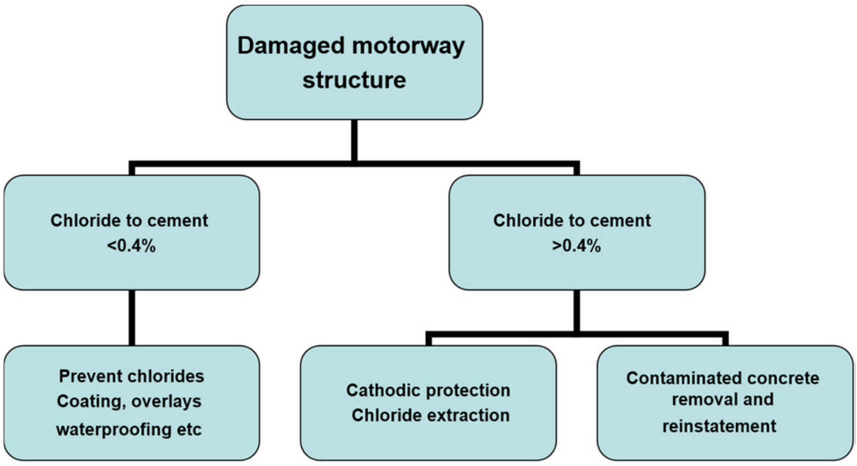
Impact of Corrosion of Steel in Concrete

23

Impact of Corrosion of Steel in Concrete

24

Repair Options and Considerations



25

BS EN 1504 - Products and systems for the repair and protection of concrete structures-Definitions, requirements, quality control and evaluation conformity

Coating Protection is repair principal No 1 in BS EN 1504 part 9

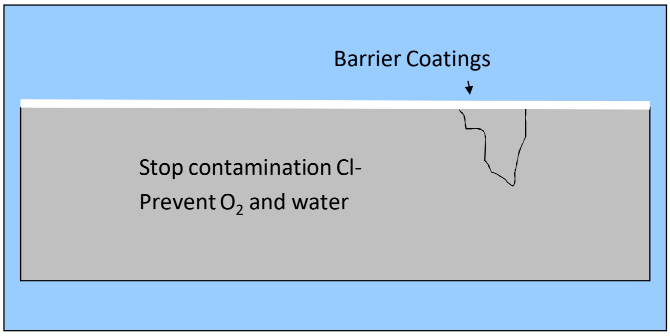
Methods to satisfy principle 1 – Protection against ingress

The following methods satisfy the principle of reducing or preventing the ingress of adverse agents e.g. water, other liquids, vapour gas such as carbon dioxide, chemicals such as chlorides and biological agents.

26

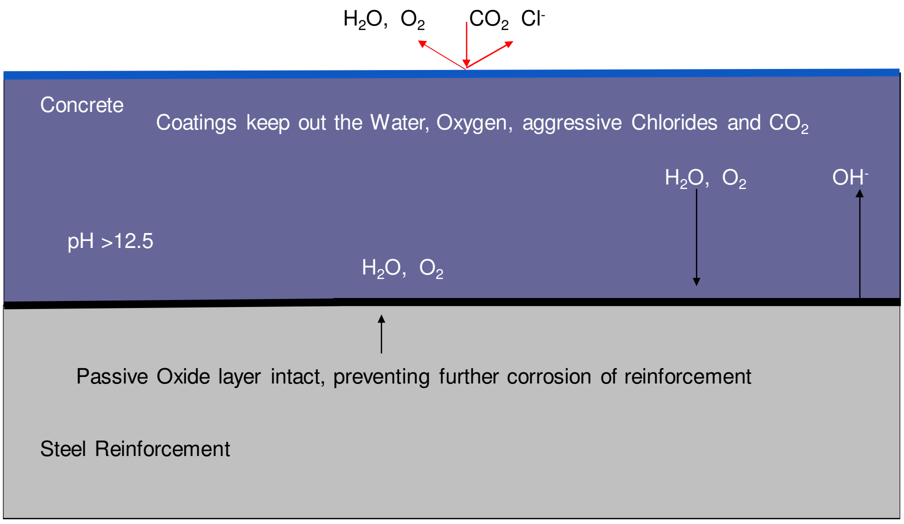
Barrier Coatings

- Painted steel
- Painted or sealed concrete- keep out CO_2 and Cl^-
- Corrosion resistant alloys Ti, Al, NiCr-alloys



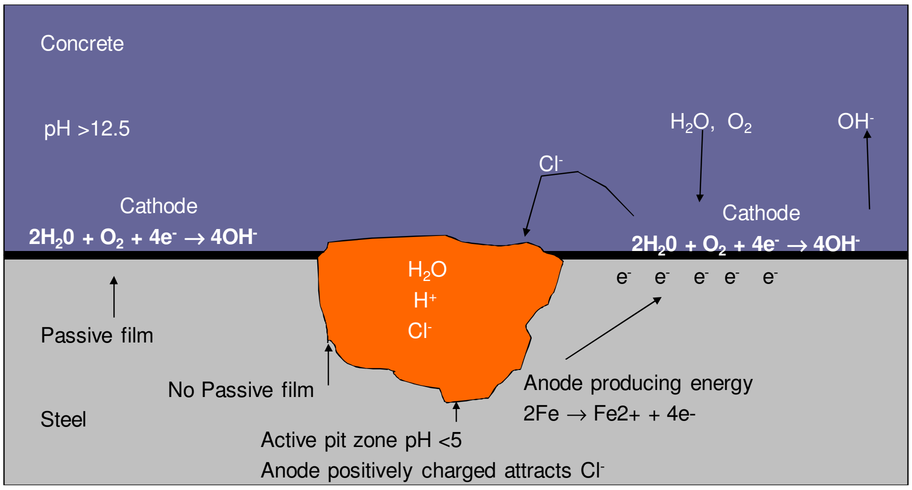
27

Coating Concrete



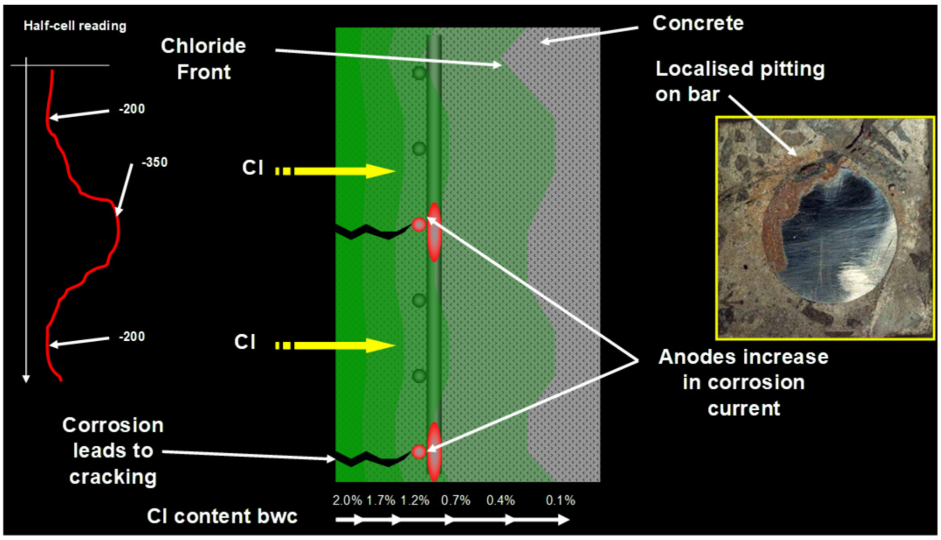
28

Cl- < 0.4 % - Chloride induced Pitting



29

Problems with Patch Repairs – Cl^- Ingress



30

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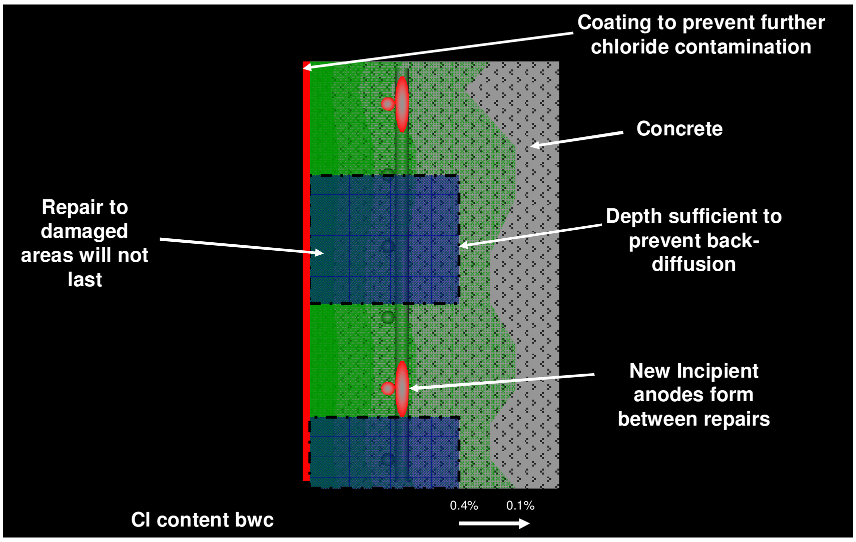
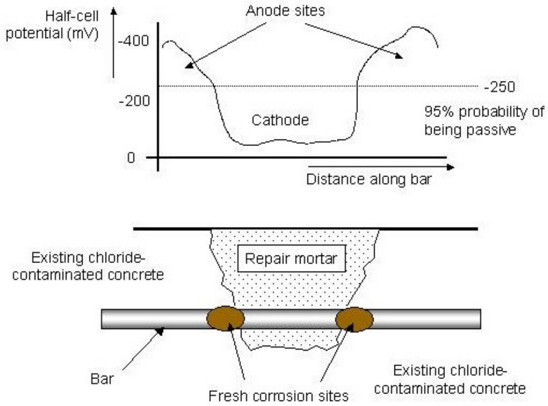


31

Incipient Anode Effect At Patch Repairs

- Caused by concentration gradients between new and old material
- Old material high chlorides, low pH becomes anodic
- New material low chlorides, high pH becomes cathodic



32

Incipient Anodes

- Ongoing corrosion
- Further delamination
- Repeat repairs

33

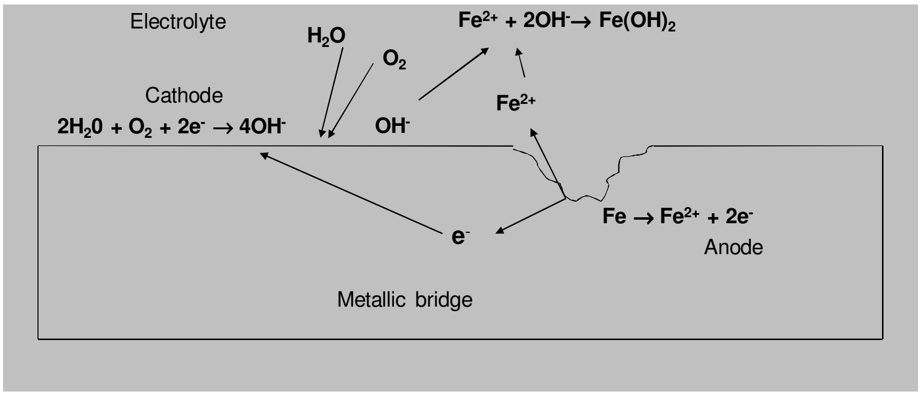
BS EN 1504 - Products and systems for the repair and protection of concrete structures-Definitions, requirements, quality control and evaluation conformity

Cathodic Protection is repair principal No 10 in BS EN 1504 part 9

9.1	**Limiting oxygen content (at the cathode) by saturation or surface coating**			
	Saturation.	7.1, 7.2.1, 7.2.2	**The concrete shall be continuously saturated with water**	9.1, 9.2
	Surface coating.	7.1, 7.2.1, 7.2.2	8.1, 8.2.1, 8.2.7	9.1, 9.2
	Method to satisfy principle 10 – Cathodic protection			
10.1	**Applying electrical potential**	See EN 12696	See EN 12696	See EN 12696 and 9.1, 9.2

34

Simple Corrosion Cell

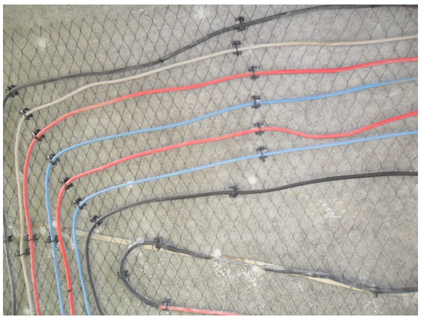


- We need all four elements for corrosion to occur
- Removal of any one will stop the corrosion process

35

Cathodic Protection

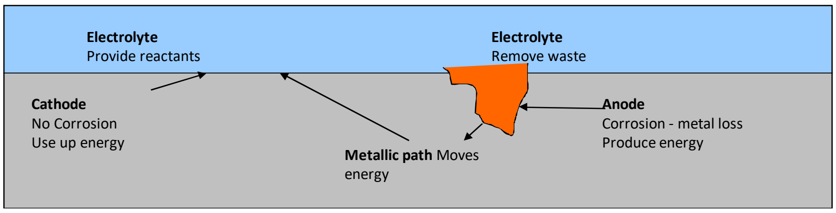
- Manipulates the corrosion reaction
- Provides the structure we aim to protect with an excess of free energy
- Promotes only the cathodic reaction on the structure we are protecting
- Controls the anode where the energy and metal loss occurs



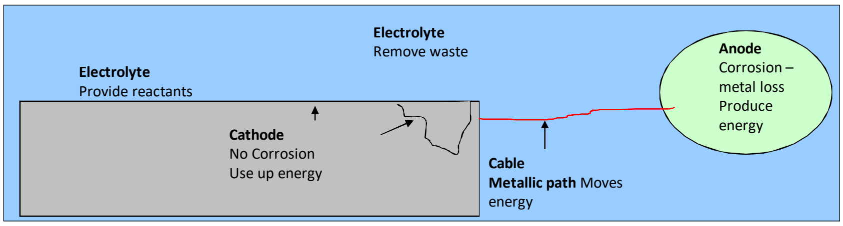
36

Cathodic Protection of Metallic Elements

- Without Cathodic Protection

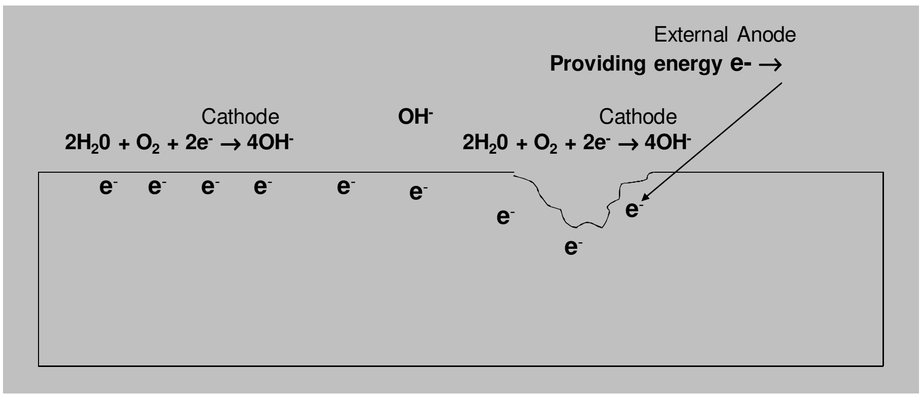


- With Cathodic Protection



37

Effect of Cathodic Protection

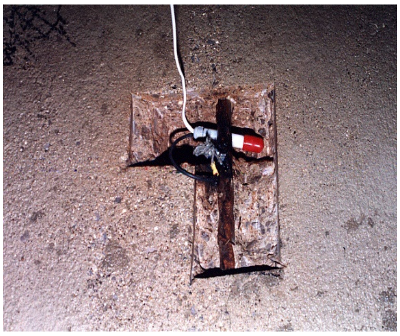


- Only the Cathode reaction on the steel surface – Consumption of Energy
- Generation of Hydroxide on the steel surface - Environment + Energy → OH^-

38

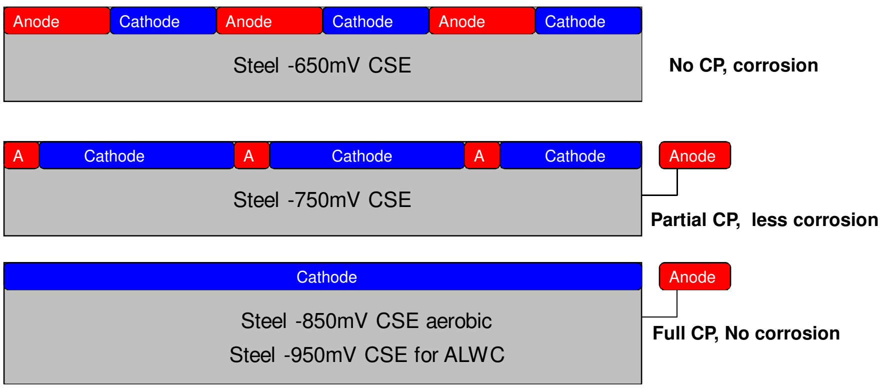
Measuring Protection

- Difference in energy (voltage) is easy to measure
  - Use a reference electrode to measure the change in energy
  - Typical reference electrodes include Silver silver chloride or Manganese dioxide.



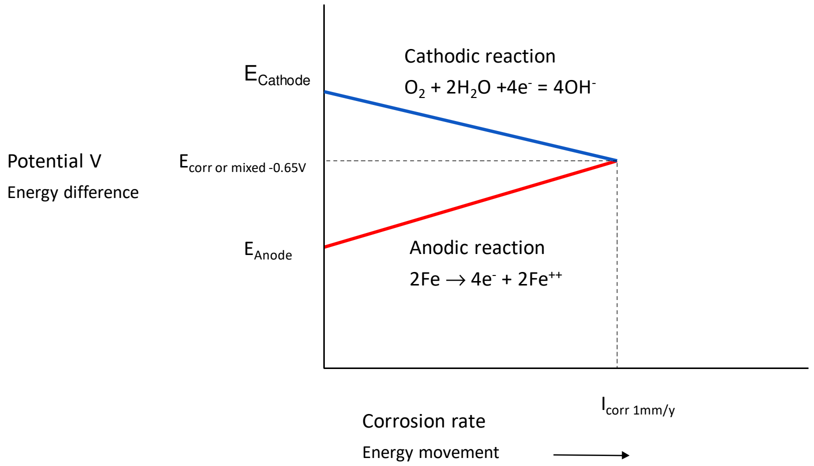
39

Effects of Cathodic Protection



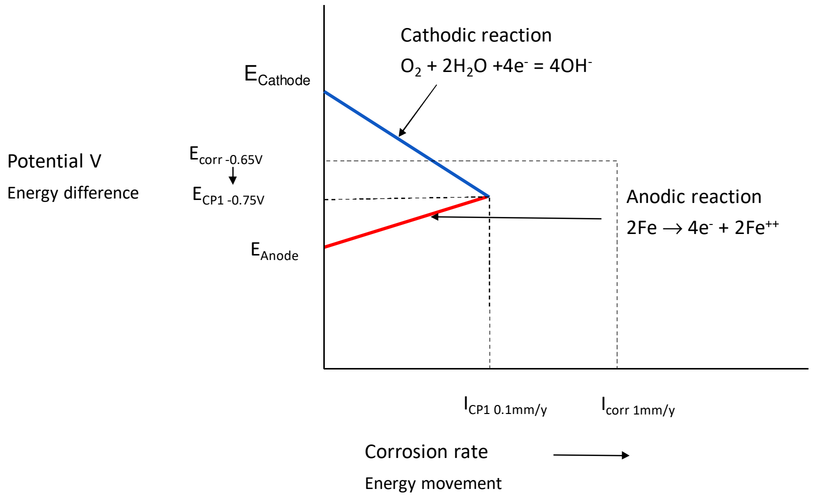
40

Effects of Cathodic Protection



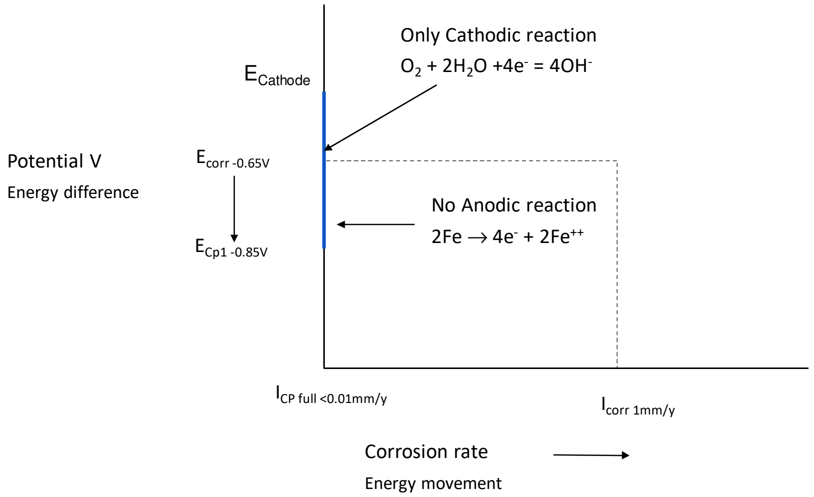
41

Effects of Cathodic Protection



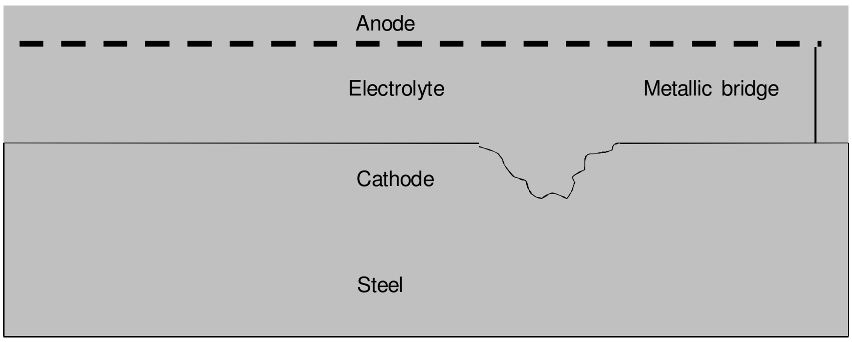
42

Effects of Cathodic Protection



43

Cathodic Protection in Concrete

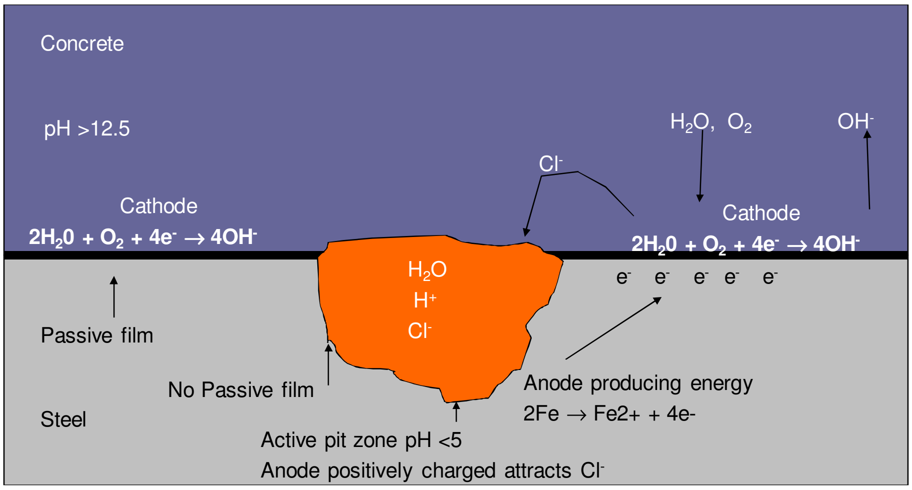


- Anode
- Cathode
- Electrolyte
- Metallic Bridge

- Still a corrosion reaction
- Needs all four parts to work
- Can not work across an air gap
- Only can protect the surface

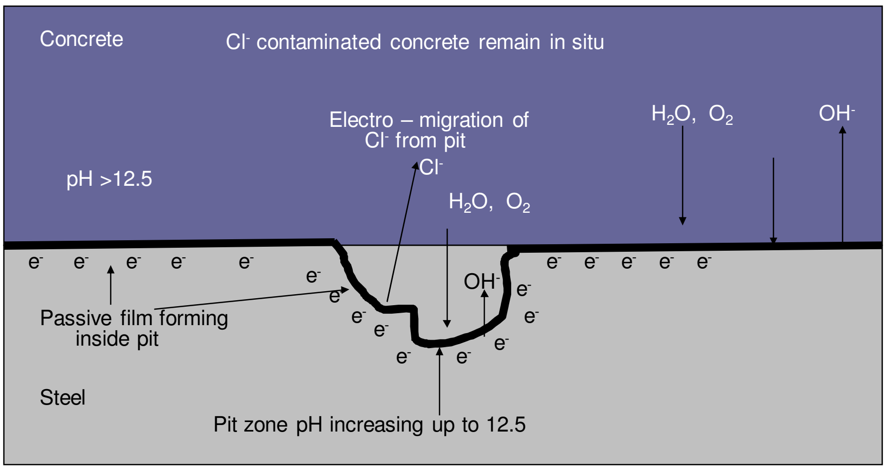
44

Chloride Induced Pitting Corrosion of Steel in Concrete



45

Cathodic Protection of Chloride Induced Pitting Corrosion of Steel in Concrete



46

Methods of Providing the Energy

Galvanic

Impressed Current

47

Methods of Providing the Energy

- Galvanic
  - Based on the potential difference between different metals
  - Limited current and driving voltage
  - Zinc, Aluminium, Magnesium and Iron

- Referred to as sacrificial protection
  - Anode material is designed to corrode and provide energy
  - Anode mass is proportionate to life

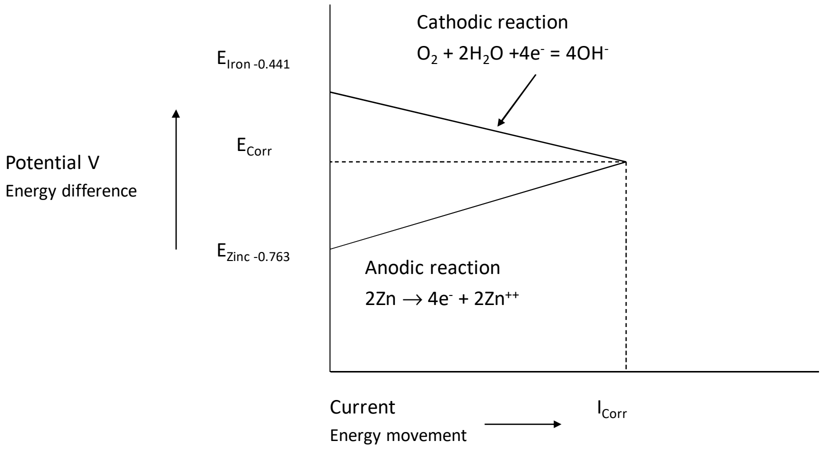
48

Electrochemical Series in Aerated Water

Reaction	Volt to standard hydrogen electrode
$Au^{3+} + 3e^- = Au$	1.520
$Ag^+ + e^- = Ag$	0.799
$O_2 + 2H_2O + 4e^- = 4OH^-$	0.401
$Cu^{2+} + 2e^- = Cu$	0.342
$Ti2^+ + 2e^- = Ti$	-0.163
$Fe^{2+} + 2e^- = Fe$	-0.441
$Zn^{2+} + 2e^- = Zn$	-0.762
$Al^{3+} + 3e^- = Al$	-1.676
$Mg^{2+} + 2e^- = Mg$	-2.356

49

Galvanic Cathodic Protection Polarisation Diagram



50

Galvanic Anodes



51

Methods of Providing the Energy - ICCP

- Impressed current
  - Anode material based on light weight stable noble material – MMO coated titanium, graphite etc
  - Steel is anodic to these anode materials
  - External energy is required to force steel cathodic
- Requires a continuous source of energy
  - Based on external power supplied from mains AC which is transformed and rectified into DC
  - Voltage and current can be adjusted up to the power supply limit

52

Electrochemical Series in Aerated Water

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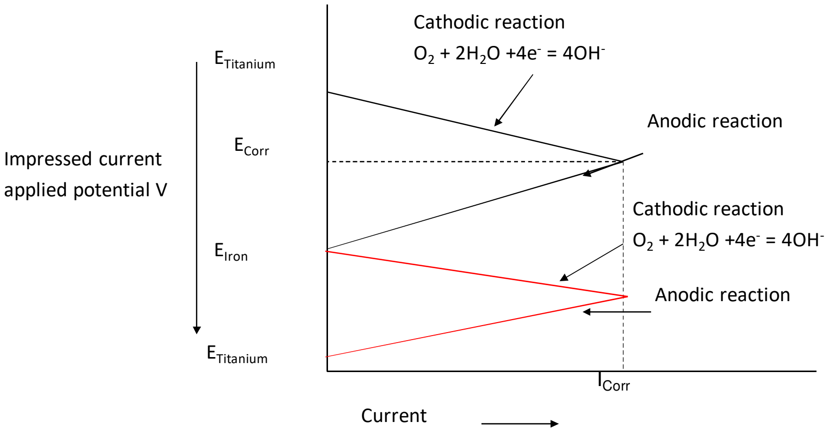
53

Impressed Cathodic Protection Polarisation Diagram



54

Impressed Current Anodes

55

Impressed Current Power Supply

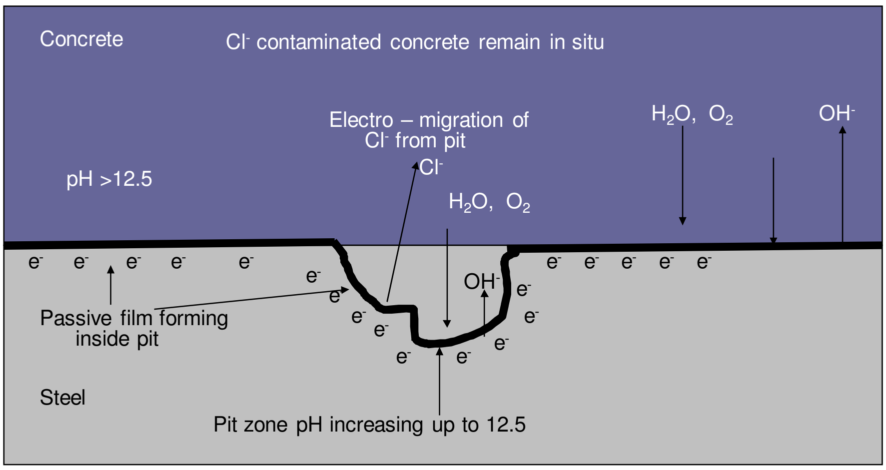
56

Benefits of – Cathodic Protection

- Reduce repairs to only damaged, spalled concrete, no need to remove contaminated sound concrete
- Capable of stopping and preventing corrosion within active pits
- Secondary benefits due to boosting of the hydroxide levels at the bar and the movement of residual chloride ion away from the steel
- Will continue to work, no matter how much salt is delivered, keeps steel negative and repels the chloride ion
- Can be effectively evaluated and assessed against international standards, using embedded reference electrodes to prove no corrosion – no need to break open and look

57

Cathodic Protection of Chloride Induced Pitting Corrosion of Steel in Concrete



58

Status of the M1 Bridges

Strategic M1 motorway bridges are more than 50 years old

Critical elements have been exposed to 50 years of chloride based winter treatment

Corrosion of reinforcement due to leaking joints and chloride contamination are a major issue

59

Consideration

- Stop and prevent further corrosion of the embedded reinforcement in chloride contaminated concrete
- Prevent future concrete deterioration due to cracking and spalling
- Would be **effective for inaccessible areas**
- **Limit** the extent of **concrete removal** and repairs required
- Implemented on a live motorway, with **no impact to traffic flow**
- **Corrosion prevention** is expected to continue **under future joint leakage**
- Relatively long design lives are possible (50 years) with only localized equipment replacement at road level at 15 year intervals

60

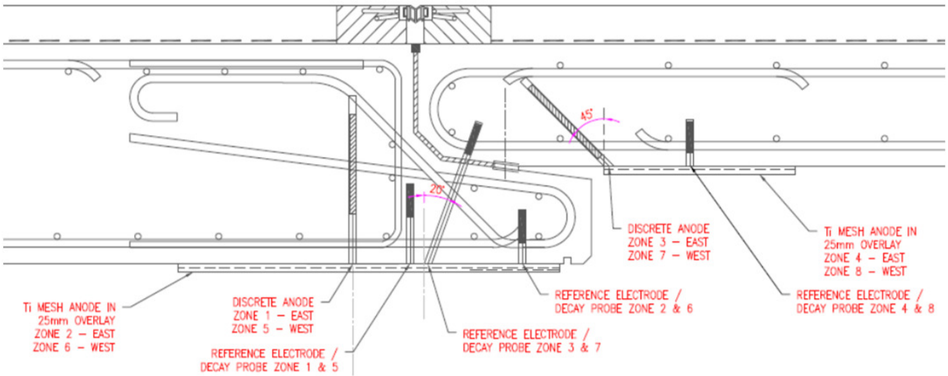
The Solution – Impressed Current Cathodic Protection

- Keep existing intact chloride contaminated concrete
- Repair only spalled or delaminated concrete –
  - Reduced structural impact, Only need access from the bottom while motorway is live
- Combination of high output, low impact anode types to address surface and inaccessible areas
- ICCP is adjustable allows for increased output under future joint leakage
- Embedded monitoring reference electrodes – demonstrate risk control of inaccessible areas against BS EN ISO 12696, no need for risk based inspection of these areas
- Equipment located on hard shoulder to facilitate repair and replacement
- Remote monitoring fitted to reduce site visits and associated H&S risk of hard shoulder access

61

Design Approach

- Discrete anodes-to protect deep steel
- Mesh anodes with sprayed concrete overlay-to protect the lower mat of steel
- Monitoring clusters at critical areas to evaluate protection



62

Surface Preparation and Discrete Anode Installation

63

Discrete Anode Installation

64

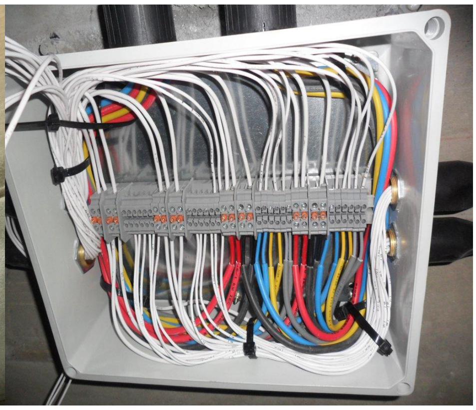
Mesh Installation and Sprayed Concrete Overlay

65

Spray Concrete Application and Finish

66

Junction Box Details and Wiring



67

Cable management and Control Equipment

68

No Traffic Impact During Installation

69

Overview

- Completed systems protecting 6 half joints were commissioned on the 29th November 2013
- To date all embedded monitoring clusters are meeting the protection criteria listed with BS EN ISO 12696 Cathodic Protection of Steel in Concrete
- Meeting the criteria listed in BS EN ISO 12696 demonstrates corrosion mitigation and control of critical reinforcement within the half joints
- Power consumption for each half joint is approximately 100 watts
- In 2014/2015 a further 14 half joints were fitted with this design and successfully commissioned

70

Status of the A19 MEL Bridge

Corrosion of reinforcement due to leaking joints and spray from passing traffic, chloride contamination a major issue

Strategic bridge carrying the A19 over a service road built in 1969

Critical elements have been exposed to 47 years of chloride based winter treatment

71

Considerations

- Large scale cover concrete removal required due to extent of spalling and existing features
- **Easy access** for inspection and repair in the future
- No AC available
- Bearing shelves **previously strengthened**
- Implemented on a live motorway, with no impact to traffic flow
- **Corrosion control** is expected to continue under future joint leakage
- Design lives in the order of 10-15 years prior to onset of cracking are expected

72

The Solution – Galvanic Cathodic Protection

- Large scale cover concrete removal will expose first layer of steel enabling anode installation and encapsulation
- Slow down the corrosion of embedded reinforcement in chloride contaminated concrete
- Prevent future concrete deterioration due to incipient anode formation at old new concrete
- Opportunity to evaluate actual galvanic anode performance

73

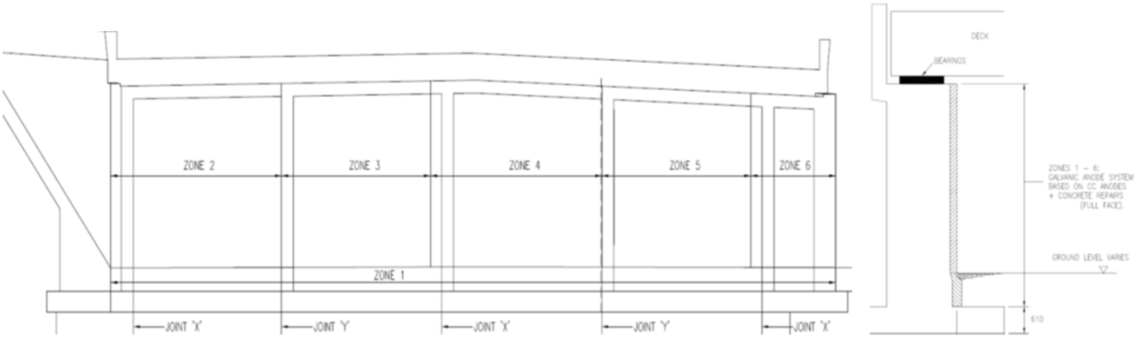
Design Approach

- Discrete galvanic anodes installed to protect the second layer of steel in chloride contaminated concrete
- Individual anodes wired-up to enable accurate performance assessment of anodes
- Monitoring clusters installed to enable accurate performance assessment against BS EN ISO 12696

74

System Zoning

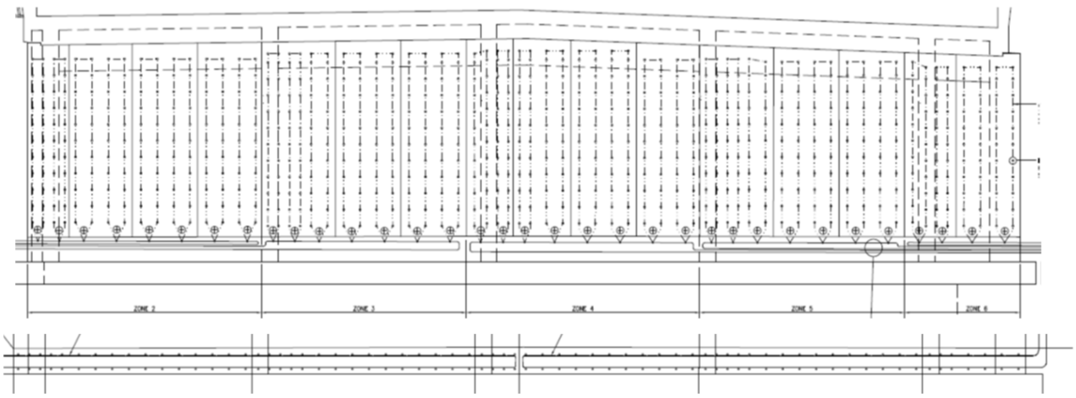
- System zoned to account for expansion joints and atmospheric or burial exposure



75

Anode Wiring

- Discrete galvanic anodes wired-up into individual anode zones to enable complete anode to cathode isolation and system performance assessment



76

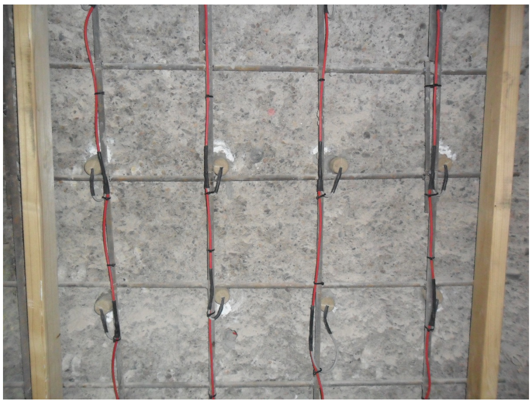
Steel Replacement

77

Electrical Continuity Bonding and Negatives

78

Discrete Anode Installation and Wiring



79

Sprayed Concrete Repair and Encasement

80

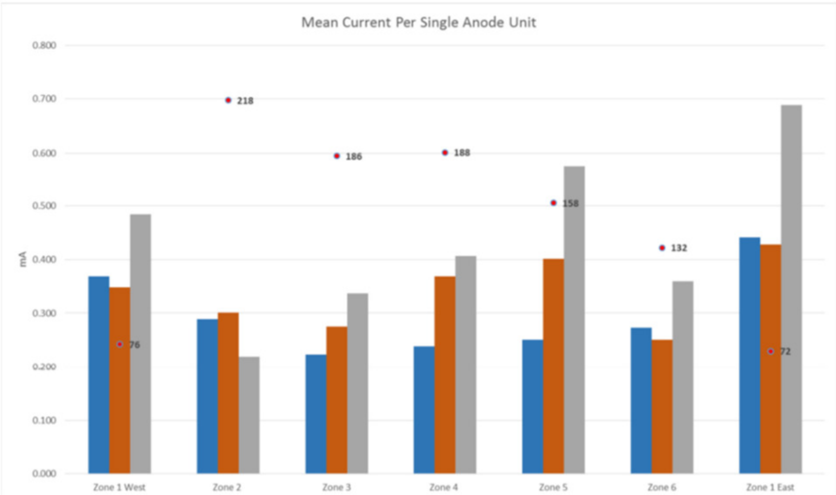
Monitoring Box and Cable Termination

81

Before and After Repairs

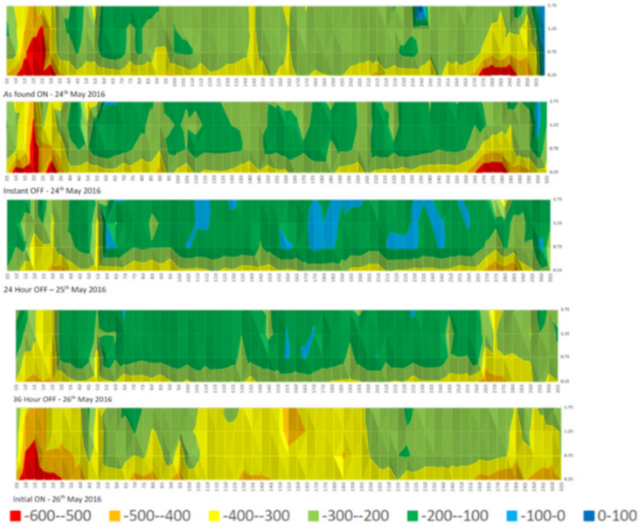
82

Performance Monitoring



83

Performance Monitoring – Potential Map



84

Overview

- System completed and commissioned March 2016
- Embedded monitoring clusters did not meet the 100mV protection criteria listed with BS EN ISO 12696 Cathodic Protection of Steel in Concrete
- Although not achieving full CP as per the requirements of BS EN ISO 12696, the system is providing corrosion mitigation of the embedded steel

85

Questions

86

Thank You

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SEGCORR Corrosion & CP Specialists

87