Sustainable Tools
Introduction to Corrosion & Cathodic Protection

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Global Implications of Corrosion

- Not sustainable
- More CO_2
  - New steel, cement, zinc, paints (hydrocarbons)
  - Transport, removal and replacement
  - Combined steel and cement production –
  - Approximately 8942 million tons in 2015 compared with 4588 million tons in 2006
- Use more natural resources
  - Iron ore
  - Lime stone
  - Coal
- Recyclability
  - Reduced or no material remains for recycling

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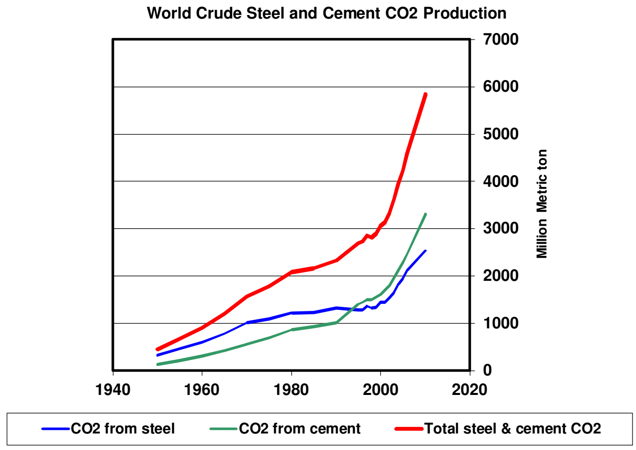
CO_2 from Steel and Cement Production



Total combined steel and cement production in 2015 was approximately 8,942 million tons of CO_2 and continues to increase. (5,843 in 2010, 4,588 in 2006).

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Local Implications of Corrosion

- Reduced operational life
- Risk to life
- Environmental and financial cost
- Maintenance down time
- Impact on traffic flow, pollution etc
- Whole life cost

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What is Corrosion

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Corrosion Definition

- A reaction between a refined metal and the environment

- Causes
  - Metal loss / degradation
  - Modification of the environment – pH, ions etc

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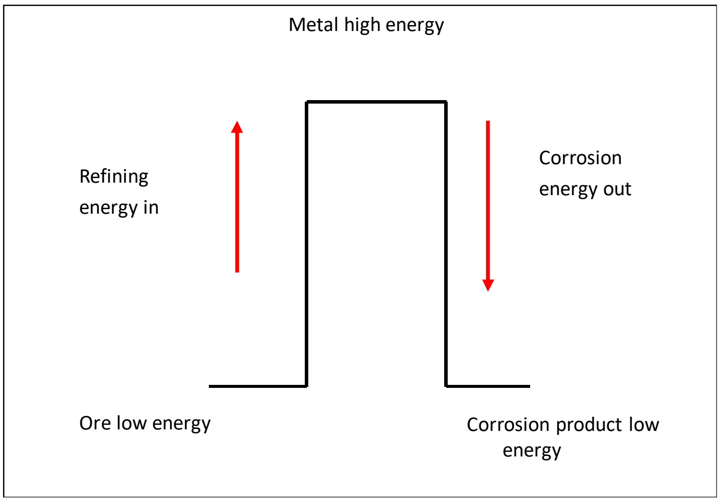
Simple Energy Diagram



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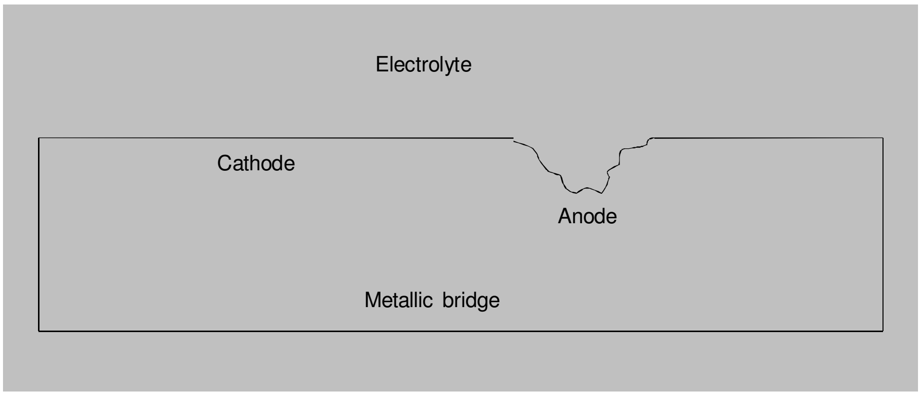
Simple Corrosion Cell



- Anode
- Cathode
- Electrolyte
- Metallic Bridge

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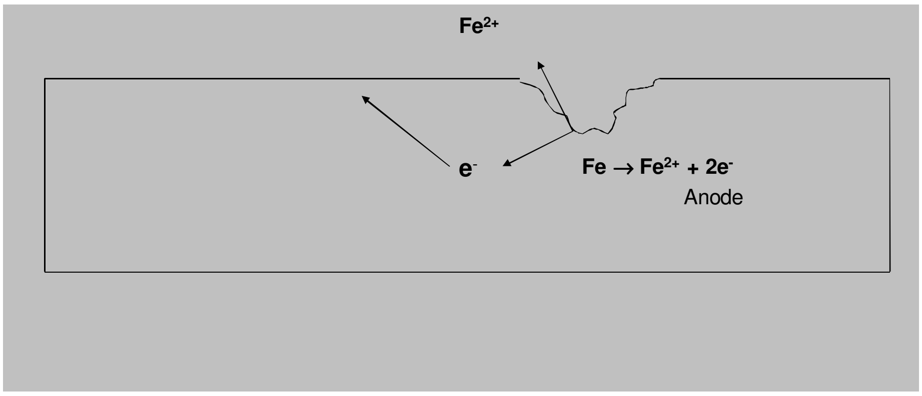
Simple Corrosion Cell



- Anode – Energy production
- Metal → Energy + Metal with less energy (m → e- + m2+)

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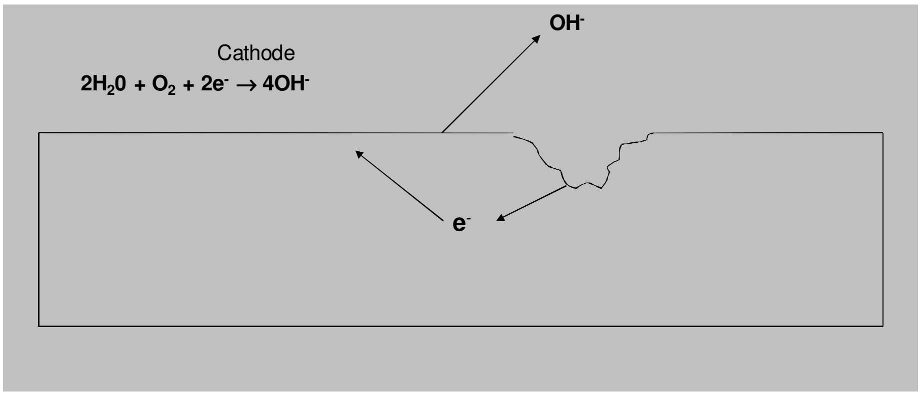
Simple Corrosion Cell



- Cathode – Consumption of energy
- Environment + Energy → Environment uses up energy and produces new product

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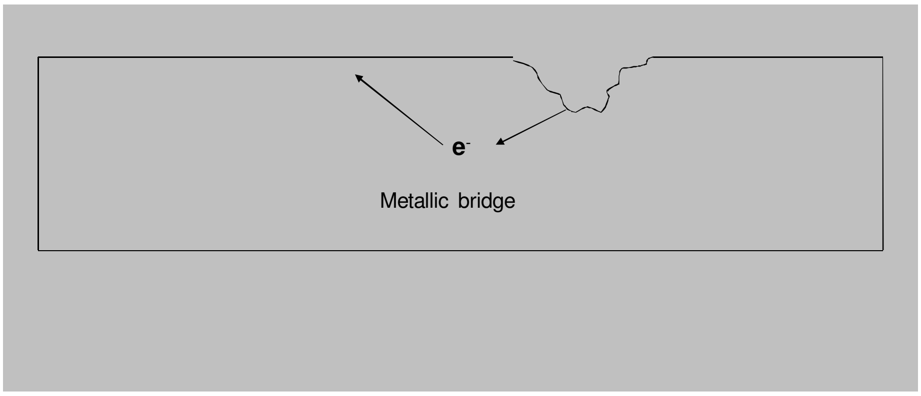
Simple Corrosion Cell



- Metallic Bridge – Energy transport

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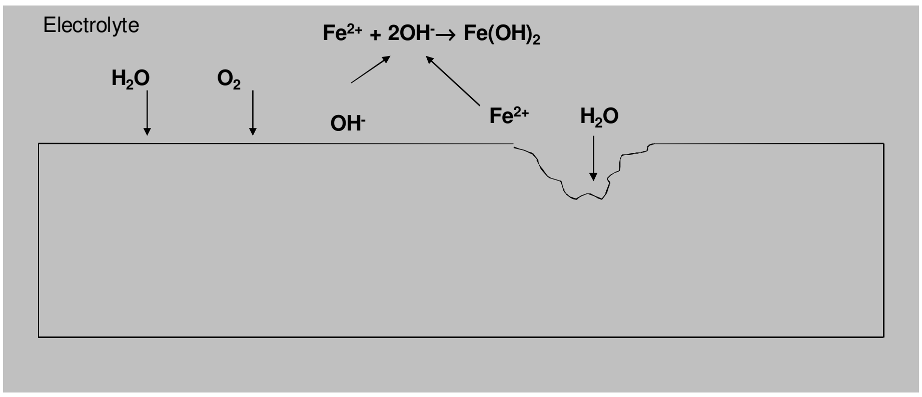
Simple Corrosion Cell



- Electrolyte - Transport of reactants to the surface
- - Removal of products from the surface

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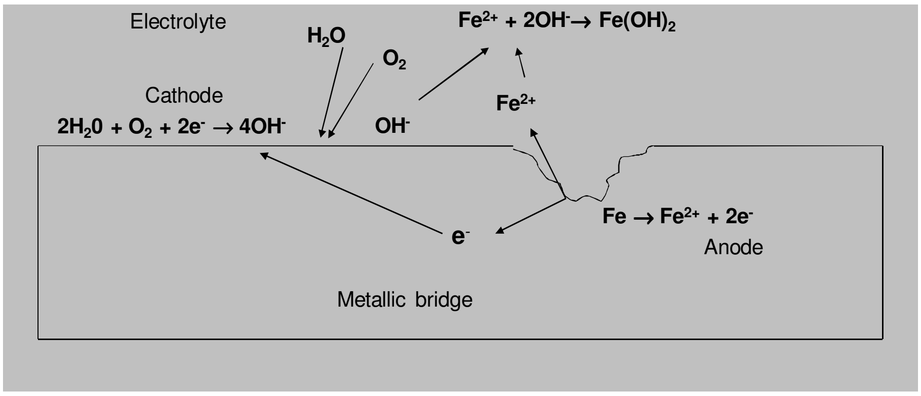
Simple Corrosion Cell



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

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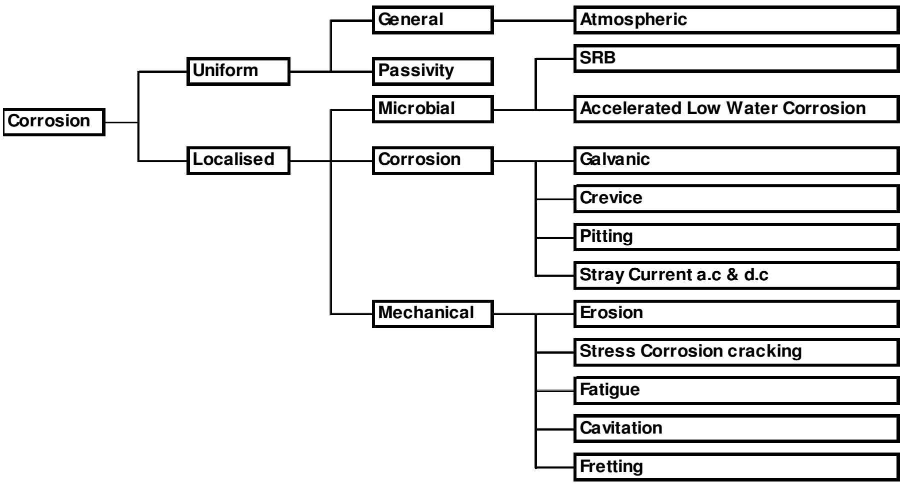
Types of Corrosion



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ALWC

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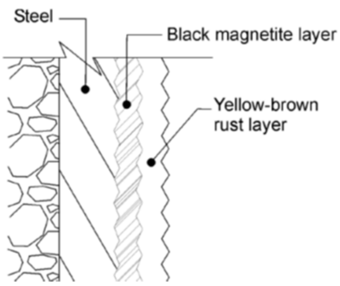
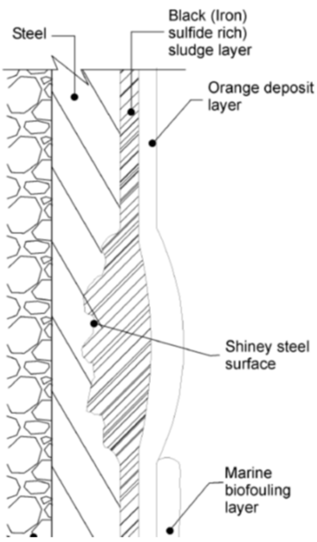
ALWC





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ALWC

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ALWC

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Protection of Steel by 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

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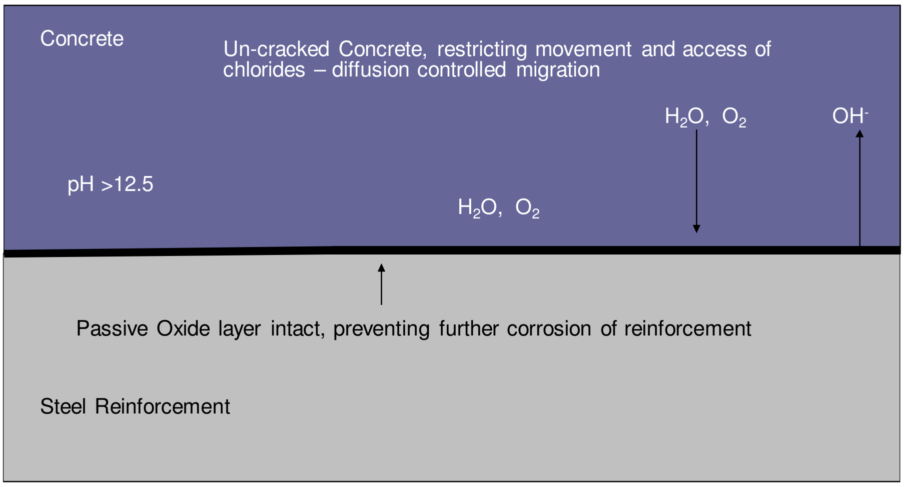
Steel in Uncontaminated Concrete



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Deterioration Processes

- Chloride induced corrosion
- Carbonation

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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

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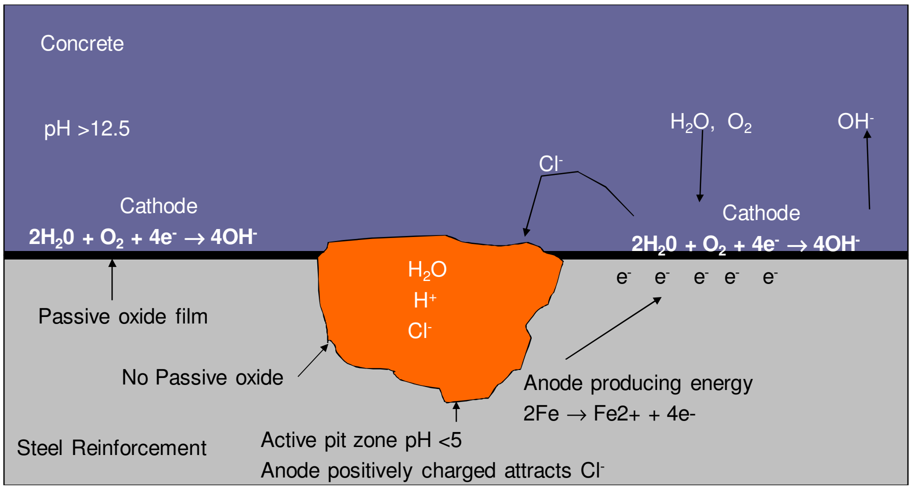
Chloride Induced Pitting Corrosion of Steel in Concrete



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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

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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

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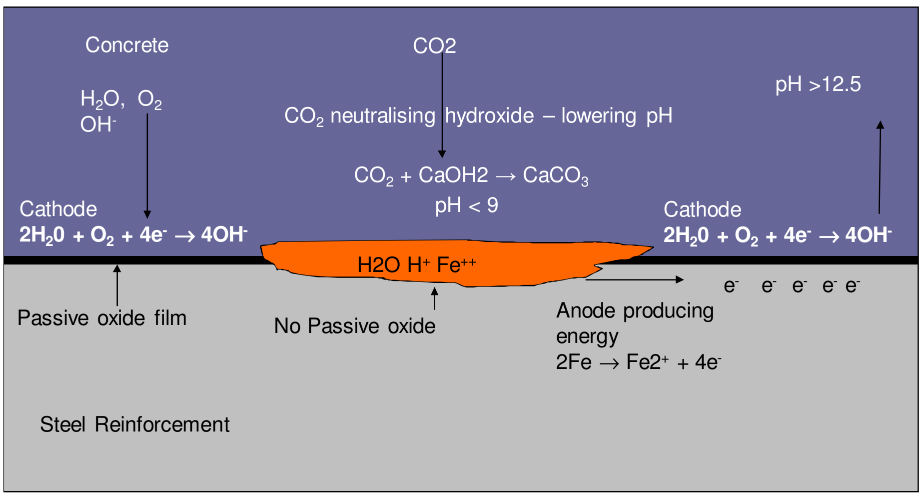
Carbonation Induced Corrosion



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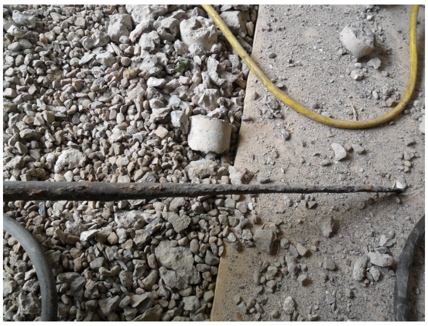
Carbonation Induced Corrosion of Steel in Concrete

- 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



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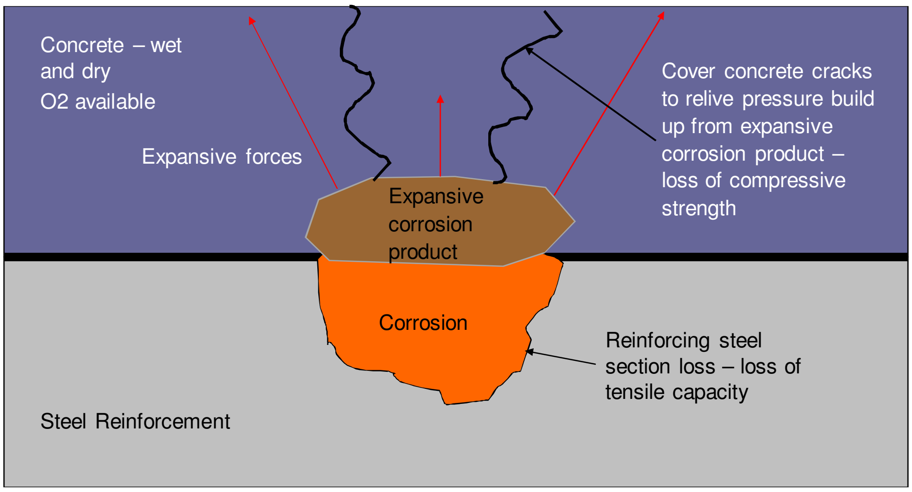
Impact of Corrosion of Steel in Concrete with O_2



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Impact of Corrosion of Steel in Concrete

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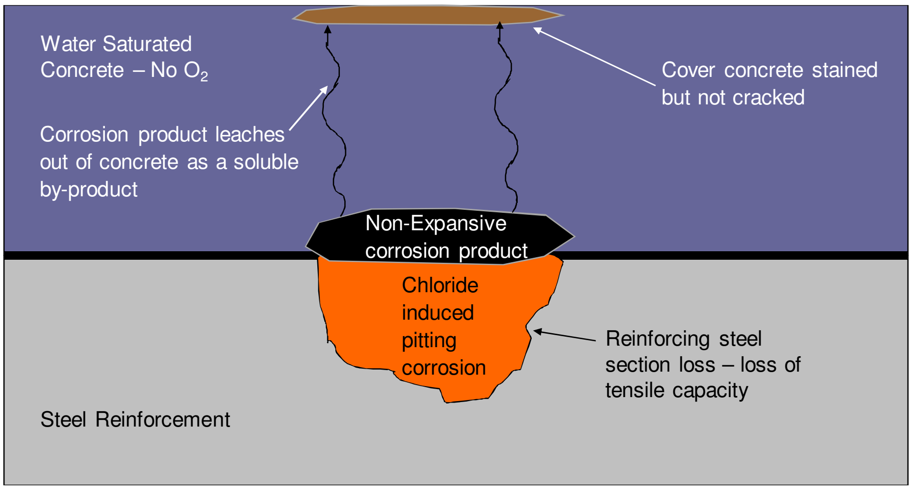
Impact of Corrosion of Steel in Concrete - No O_2



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Impact of Corrosion of Steel in Concrete

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Impact of Corrosion of Steel in Concrete

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Overview

- The high pH (hydroxide content) of concrete provides corrosion protection to steel in concrete
- Chlorides don't change the pH but compete with the hydroxide and perforate the passive oxide layer, leading to pitting
- Carbon dioxide neutralises the hydroxide and lowers the pH to levels where the passive oxide is no longer stable, leading to generalised corrosion
- Expansive corrosion products (rust) cracks the cover concrete then normal aqueous corrosion continues

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Durability & Deterioration

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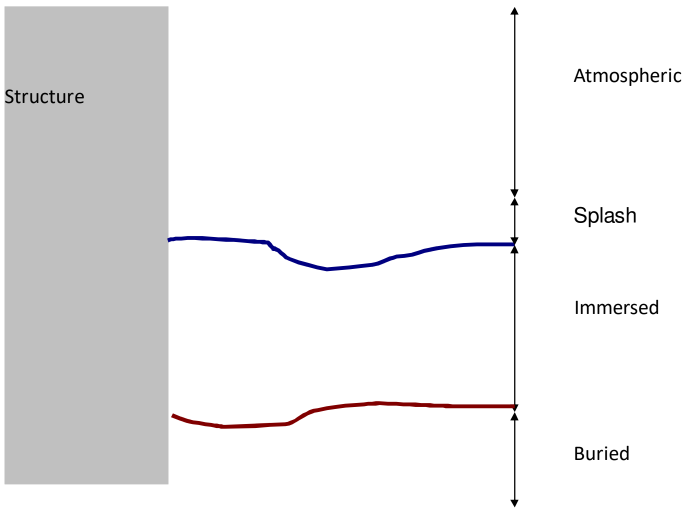
Exposure Conditions – Environment



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Atmospheric Corrosion Mild Steel

- Time of wetness
  - 100% RH condensation
  - >75% RH corrosion significant
  - <75%RH almost no corrosion
- Salts hydroscopic – wet surface
  - NaCl – 78%RH
  - CaCl2 – 35%RH
  - LiCl - <5%RH

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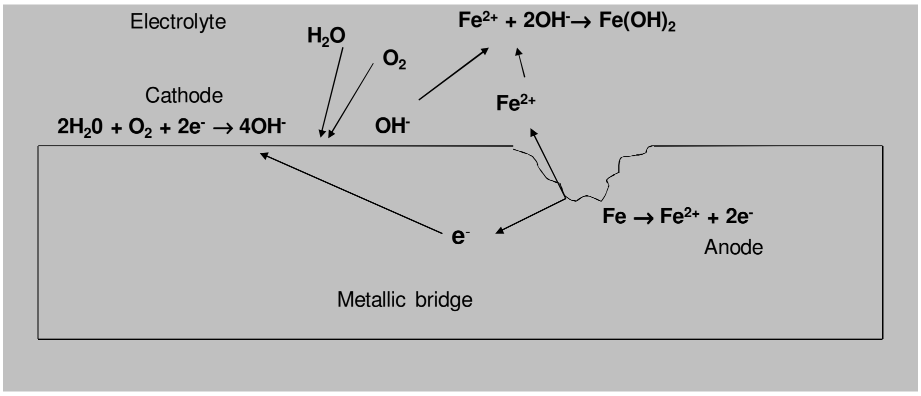
Simple Corrosion Cell



- We need all four elements for corrosion to occur
- Removal of electrolyte (metals atmospherically exposed only)

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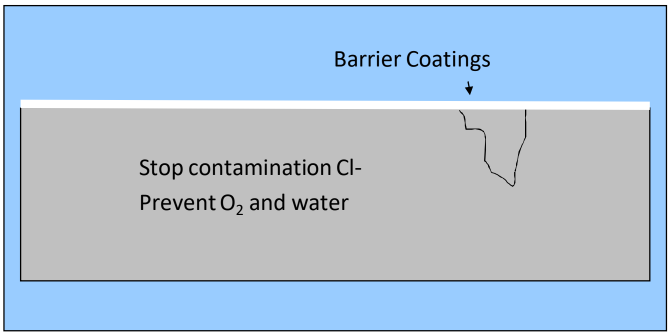
Barrier Coatings – Bare metals

- Painted steel
- Corrosion resistant alloys Ti, Al, NiCr-alloys



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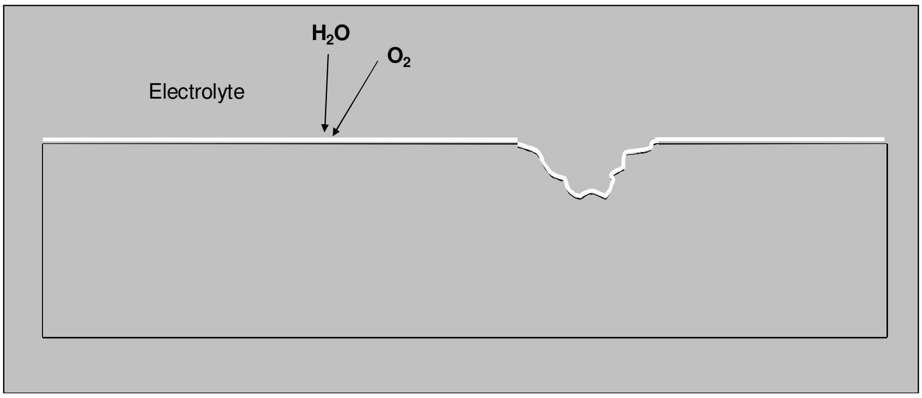
Coated Bare metal or CRA's



- Coatings remove the electrolyte of bare metals
- Stops the corrosion process as long as there are no holes in the coating

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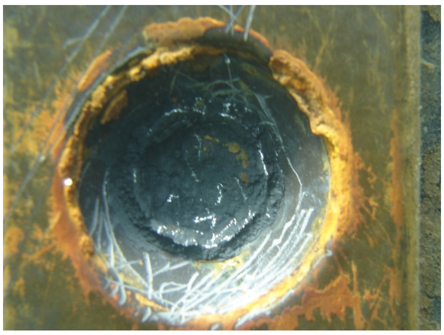
Coatings Buried and Immersed

Coatings only work where there are no Holes



Never - just coat buried or immersed structures

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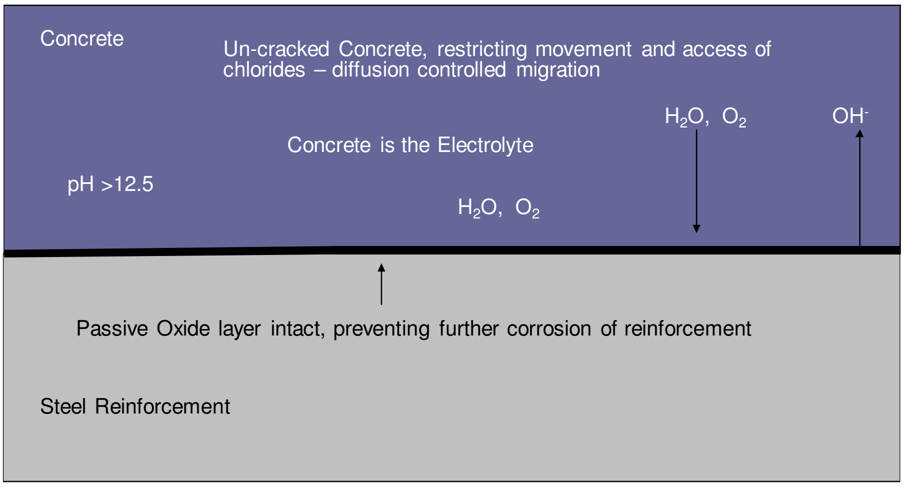
Steel in Uncontaminated Concrete



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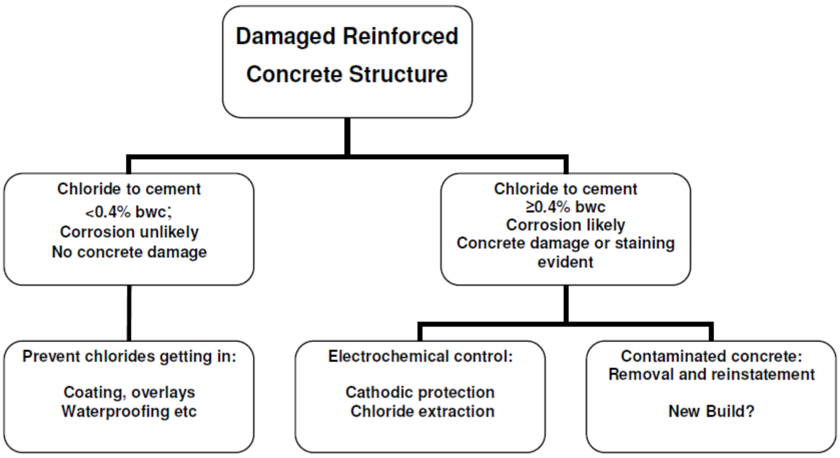
Repair Options and Considerations



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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.

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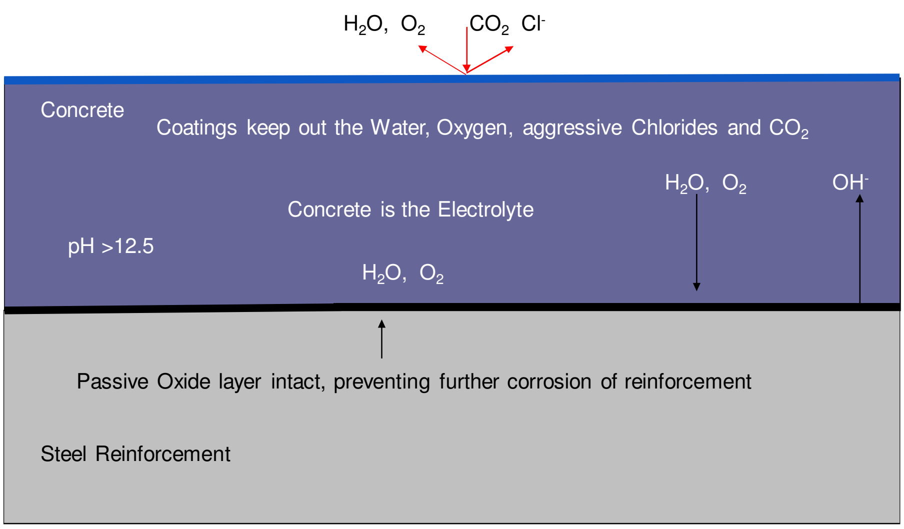
<0.4wt % Cl^- - Coating Concrete



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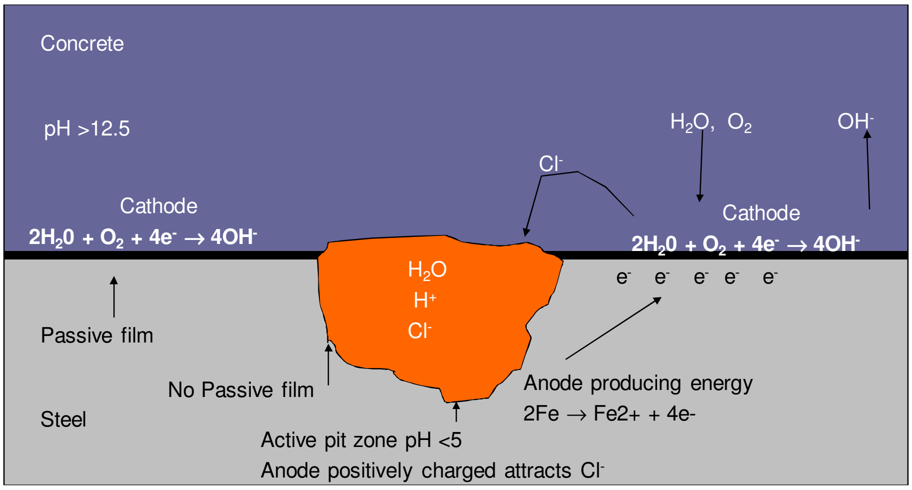
> 0.4 wt % Cl^- - Chloride Induced Pitting



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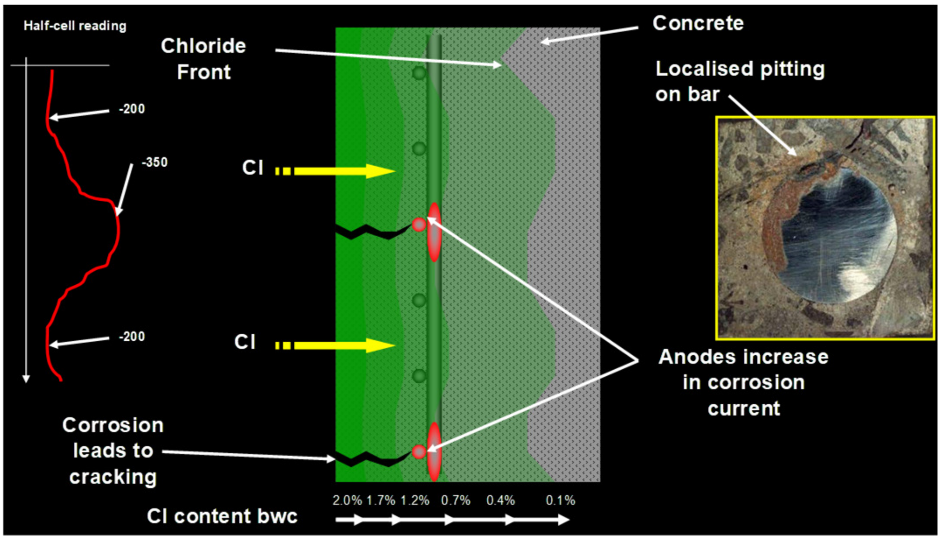
Problems with Patch Repairs – Cl^- Ingress



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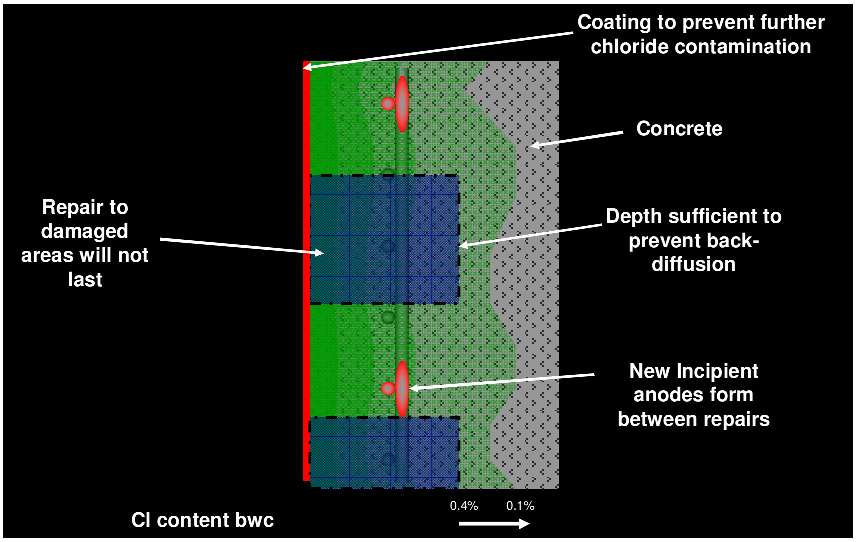
Problems with Patch Repairs – Cl^- Ingress



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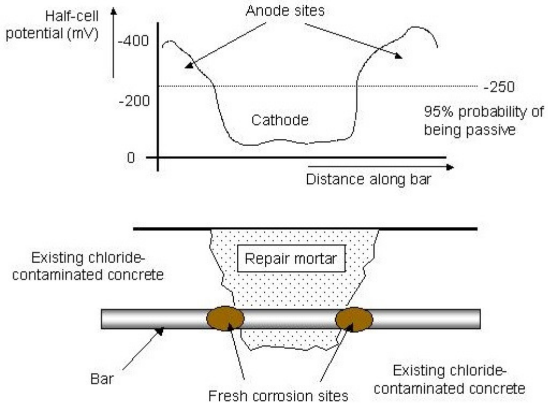
Incipient Anode Effect At Patch Repairs

- 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



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Incipient Anodes

- Ongoing corrosion
- Further delamination
- Repeat repairs

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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

	[illegible]			
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

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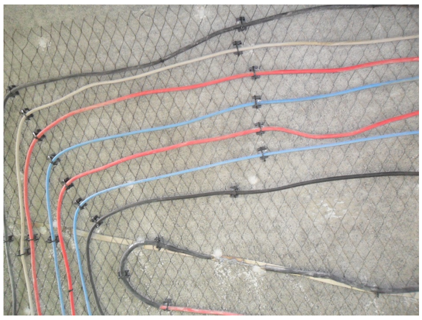
Cathodic Protection

- 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



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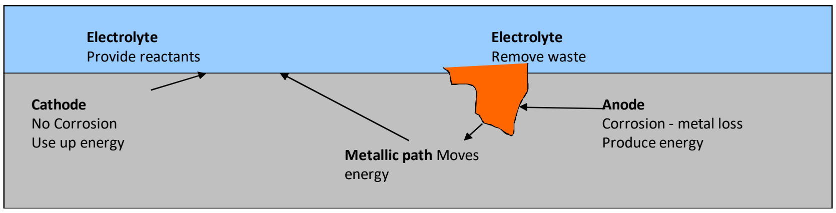
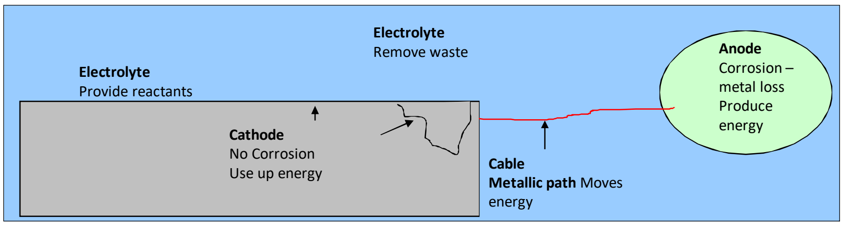
Cathodic Protection of Metallic Elements

- Without Cathodic Protection



- With Cathodic Protection



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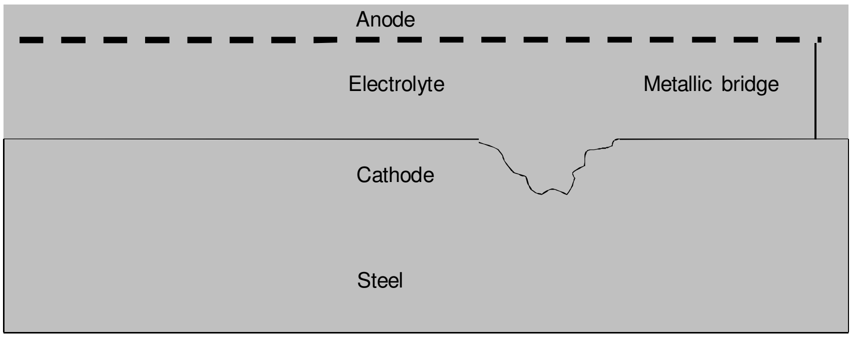
Cathodic Protection in Concrete



- 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

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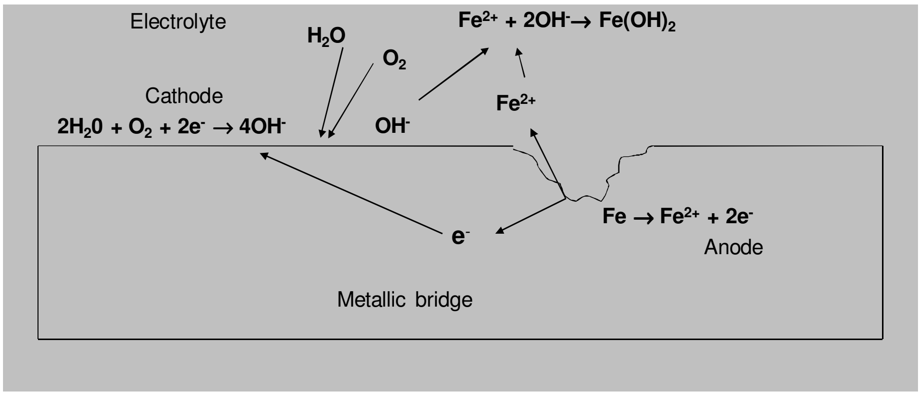
Simple Corrosion Cell



- We need all four elements for corrosion to occur
- Modify the corrosion process – via electrochemical means

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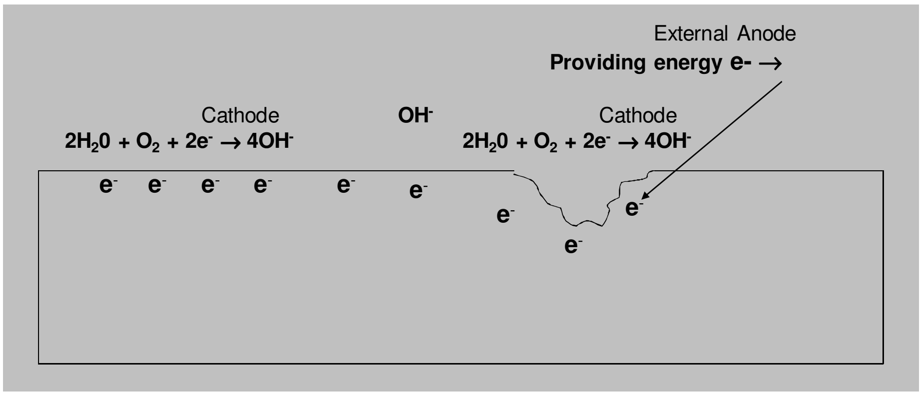
Effect of Cathodic Protection



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

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Effectiveness of Cathodic Protection

Exposure Condition	Cathodic Protection Effective		Comments
	Metallic	Reinforced Concrete	
Atmospheric	No	Yes	Metallic elements depend entirely on the barrier effects of coating systems to prevent corrosion. Reinforced concrete elements require the anodes to be installed within the concrete for the CP to work.
Splash	Partial	Yes	Metallic elements within the tidal or splash area can receive cathodic protection only during the immersed cycle this effect tends to provide intermittent protection and a combination of coating and cathodic protection is required. Reinforced concrete elements above mean low water require the anodes to be installed within the concrete, below this external anodes can be used
Immersed	Yes	Yes	External anodes can be used to provide protection to both reinforced concrete and metallic element
Buried	Yes	Yes	External anodes can be used to provide protection to both reinforced concrete and metallic element

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CP for Steel in Concrete

CP is effective for all atmospheric buried and immersed RC structures

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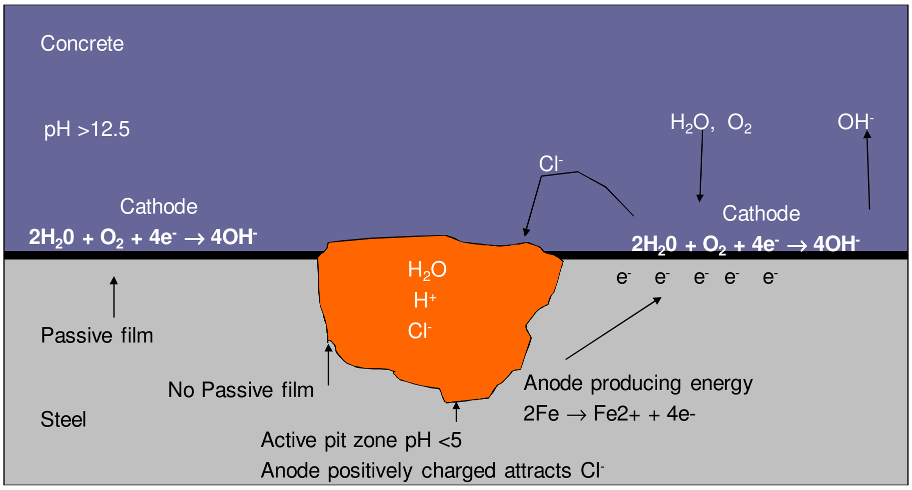
Chloride Induced Pitting Corrosion of Steel in Concrete



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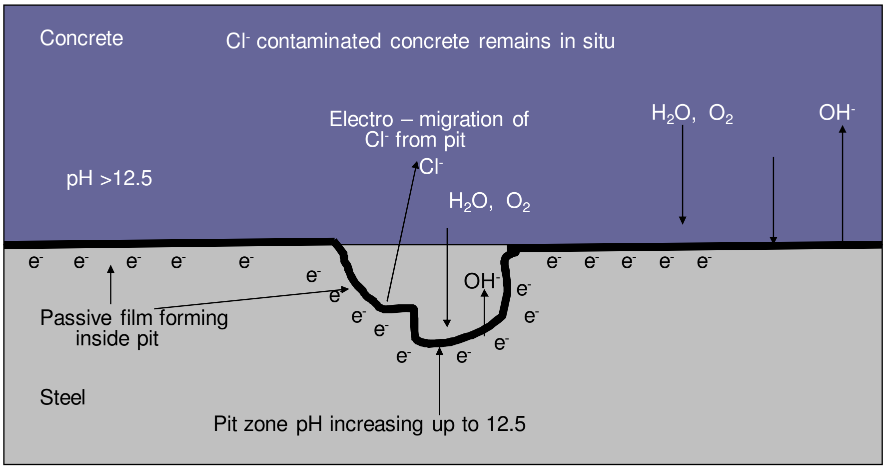
Cathodic Protection of Chloride Induced Pitting Corrosion of Steel in Concrete



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CP for Buried and Immersed

CP is effective for all buried and immersed - bare or coated structures

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CP & Coatings – Synergy

- CP protects the pin holes or coating defects
- CP stops the coatings deteriorating
- Coatings reduce the amount of energy needed
  - Less anodes, less cost, longer life

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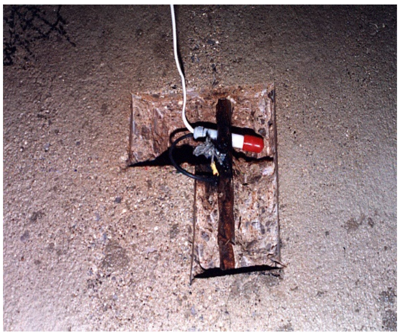
Measuring Protection

- 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.



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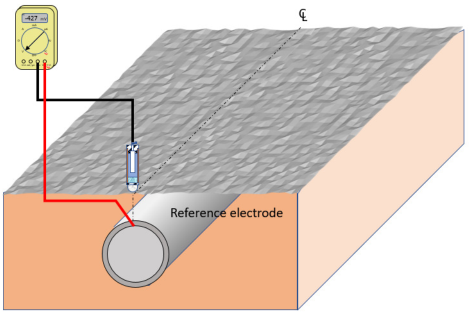
We Can Measure Cathodic Protection

- Difference in energy (voltage) is easy to measure
  - Use a reference electrode to measure the change in energy
  - Typical reference electrodes include Copper Copper sulphate (Cu/CuSO4), Silver silver chloride sea water.



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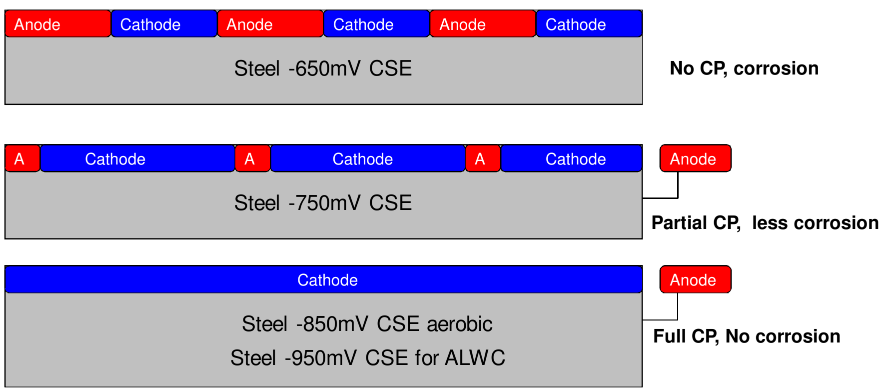
Effects of Cathodic Protection



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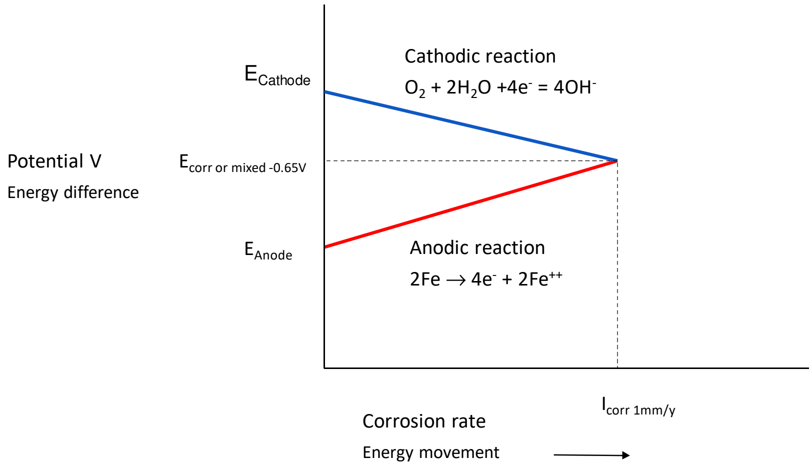
Effects of Cathodic Protection



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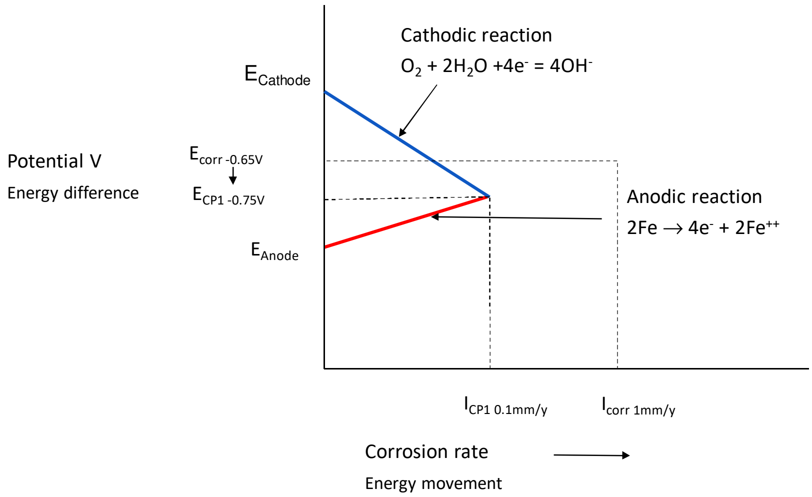
Effects of Cathodic Protection



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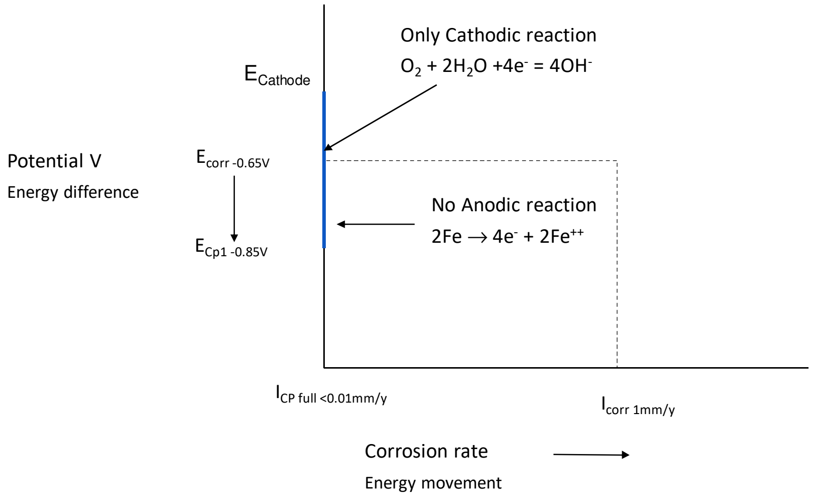
Effects of Cathodic Protection



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Methods of Providing the Energy

Galvanic

Impressed Current

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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

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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

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Galvanic Anodes

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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

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Impressed Current Anodes

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Impressed Current Power Supply

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CP Standards

BS EN 12473:2000	General principles of cathodic protection in sea water
BS EN 12474:2001	Cathodic protection for submarine pipelines
BS EN 12495:2000	Cathodic protection for fixed steel offshore structures
BS EN 12499:2003	Internal cathodic protection of metallic structures
BS EN 12696:2000	Cathodic protection of steel in concrete
BS EN 12954:2001	Cathodic protection of buried or immersed metallic structures. General principles and application for pipelines
BS EN 13173:2001	Cathodic protection for steel offshore floating structures
BS EN 13174:2001	Cathodic protection for harbour installations
BS EN 13509:2003	Cathodic protection measurement techniques
BS EN 13636:2004	Cathodic protection of buried metallic tanks and related piping
BS EN 14505:2005	Cathodic protection of complex structures
BS EN 15112:2006	External cathodic protection of well casing
BS EN 15257:2006	Cathodic protection. Competence levels and certification of cathodic protection personnel

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Example Case Study – Outfall Diffuser

- 5 km outfall pipe PE with concrete weight coating
- Land end connector and diffuser head mild steel
- Design life – minimum 80 years
- No access or Maintenance - deeper than 30m under water and partly buried in mud
- Effluent treated sewage and storm water

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Example Case Study – Outfall Diffuser

- Approach
- Land tie-in and diffuser mild steel, connection nuts stainless steel
- Mild steel coated with 2mm glass flake epoxy internal and external surfaces
- All surfaces to get galvanic CP

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Example Case Study – Outfall Diffuser

- Internals
- Water composition – can’t use galvanic aluminium must use zinc due to resistivity
- Issues with flow and cavitation – minimise size of anodes
- Limits anode life to 30 years max
- Corrosion allowance of pipe wall 50 years inside out

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Example Case Study – Outfall Diffuser

- External
- Sea water and mud use galvanic aluminium
- Limits anode life to 60 years max due to weight
- Corrosion allowance of pipe wall 20 years outside in

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Example Case Study – Outfall Diffuser

- Engineering approach
- Use non metallic PE where possible
- For metallic use high performance coating with CP
- For internals use zinc anodes due to water resistivity
- For externals use aluminium anodes
- **Last option – corrosion allowance**

- Combined approach to achieve 80 years of operation

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Effluent Outfall Galvanic CP with Coatings and Corrosion Allowance

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Example Case Study – Port Rehabilitation

- 50 year old port structures including steel and RC
- Structures in a deteriorated state
- Client need new cranes
- Original structural capacity required
- Client would like a 50 year life extension following repairs

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Example Case Study – Port Rehabilitation

- Reinforced Concrete full of chlorides
- Cover concrete missing
- Rebar section loss present
- Full concrete repairs and rebar replacement needed
- Issue with residual chloride and new concrete repairs
- Use ICCP to address Incipient anode and future chloride risk

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Example Case Study – Port Rehabilitation

- New rebar welded in
- Shuttered concrete repairs

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Example Case Study – Port Rehabilitation

- Impressed current cathodic protection using MMO coated titanium mesh encapsulated in sprayed concrete overlay

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Example Case Study – Port Rehabilitation

- Cable management of ICCP cables
- Stainless steel cable tray
- Non metallic boxes/ fixings

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Example Case Study – Port Rehabilitation

- Fenders corroded in atmospheric areas
- Full grit blast and 2mm Glass flake epoxy for all atmospheric areas

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Example Case Study – Port Rehabilitation

- Fenders suffering ALWC below water line
- Galvanic CP using Aluminium anodes applied to all areas below water level

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Example Case Study – Port Rehabilitation

- **Engineering approach**
- Fix all damaged concrete and replace corroded reinforcement
- Provide ICCP to all atmospherically exposed RC
- Provide galvanic CP to all immersed RC
- Protective coatings to all bare metal above mean tide
- Galvanic CP using Aluminium anodes to bare metal below mean tide

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Port Rehabilitation – ICCP, Galvanic CP and Coatings for Mixed RC and Metallic Elements

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Thank You

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