Reinforcement Corrosion, No Perfect Solution

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What is Concrete?

Concrete is economical with a long life & low maintenance
Concrete does not rot, corrode, or decay.
Concrete can be molded or cast into almost any desired shape.
Concrete is fire-safe & able withstand high temperatures.
Concrete is resistant to wind, water, rodents, and insects.

12 BILLION cu meters per year globally
~1 cu yd / person / year in USA
>70 Billion cu meters placed in USA since 1930
   with ~10 Billion cu meters > 20 years old
Definitions

- Anode (−) the electrode at which electrons are lost and oxidation occurs. This is where we see rust.
- Cathode (+) the electrode at which electrons are gained and reduction occurs.
- Electrolyte – solution containing ions (Cl⁻, OH⁻)
- Steel Reinforced concrete is a unique “battery” in that the electrolyte….

IS THE CONCRETE

...And all its components
What is the biggest ROI for concrete repair?

De Sitter’s Law of Fives

$1 spent Monitoring =

$5 spent on Preventative Maintenance Before Corrosion Initiation =

$25 spent on Repair and Maintenance after Localized Corrosion Initiation =

$125 spent on Repair & Replacement after Generalized Corrosion

Pay Me NOW

OR

Pay Me LATER

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Tuuttti Diagram

Maximum Permissible Corrosion

COST $

Proactive
Preventative
Intervention

NO Intervention

Corrosion Initiation Phase
(i.e., ingress of chloride, carbonation, etc.)

Corrosion Propagation Phase
(i.e., progressive corrosion & degradation of Reinforcement)

Service Life
Do Unto Your Future Before Your Future Does Unto YOU!

REACTIVE MAINTENANCE
Proactive Maintenance

SERVICE FAILURE

COST $

TIME

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Concrete & Reinforcement Steel
A Strong Connection

Steel strengthens concrete
- Concrete itself cannot withstand high tensile strengths
  - Usage of steel reinforcement to provide world’s most widely used building composite

Concrete protects steel
- A dense layer of cover concrete acts as a barrier to the atmosphere
- Alkalinity released during hydration sustains a stable oxide film on the surface
- Additionally, a lime rich layer forms on the steel surface, assisting passivation
Corrosion = **Iron** + **Oxygen** + **Moisture**

Either

- the pH falls due to carbonation or other chemicals
- chlorides reach the steel above the threshold concentration
- an electrical charge destroys the natural protection of the steel
- Electrons flow and ions migrate
- Rust expansion causes cracking
- Rapid deterioration
- Spalling
Corrosion of Steel in Concrete

A huge cost to society…

Key Facts:

- All steel reinforced concrete worldwide is at risk due to corrosion
- Global cost of corrosion 1 - 5% of GNP
- Global market size of corrosion mitigation in steel reinforced concrete = $1 ¼ B (1 Bn€)
- As long as we reinforce concrete with steel, it will rust.

Natural laws: Concrete cracks – steel corrodes
Corrosion of Steel in Concrete  
*Electrochemical Process and Materials Science*

**Passivation layer can be breached**
- Halide ions $> 330$ ppm
- pH value $< 10$
- In combination with Oxygen, Temperature, resistivity etc...

**Steel corrosion is the problem**
- Conversion to iron oxide which occupies 4-10 times the volume
- Internal pressure builds up, results in cracking and spalling of concrete
- Loss of strength, weakening of the concrete faster deterioration, up to failure
Corrosion:
There is no perfect Solution. We are still Learning.

Why does Corrosion Occur?

Iron Ore

Deterioration

Refining

What Can We Do?

MITIGATION

PREVENTION

PROTECTION

Steel
RUST

THE SEASONAL APOCALYPSE HAS ARRIVED

ARE YOU PREPARED?
Corrosion Management

*Essential element of sustainable strategy*

**Economy**
- Provide return on investments

**Environment**
- Protects resources

**Social Responsibility**
- Saves Lives
Anode
- Concrete Permeability
  - W/CM, Pozzolans, Chemical Additions
  - Membrane, Silane
- Corrosion Threshold
  - Inhibitor
  - Change Metal (i.e. Stainless)
- Reduce Reactive Surface
  - Coatings
- Reduce Corrosion Rate
  - Dry Out Concrete
- Force Opposite Reaction
  - Cathodic Protection

Cathode
- Reduce Area of Reactive Surface
  - Coatings
- Dry Concrete
- Reduce Oxygen
- Reduce Cathode Effectiveness
  - Inhibitors
  - Cathodic Protection

Electrical Continuity
- Disconnect Anode & Cathode
- Electrical Separation of Bars
  - Coatings

Ionic Path
- Higher Resistivity
  - Lower W/CM
  - Dry Concrete
  - SCM
Corrosion Prevention/Mitigation Strategies
“Breaking the Chain”

Mechanical/Physical
- Remove/Replace
- Barrier
- Chloride Extraction
- Alternative Materials

Electrical
- Cathodic Protection

Chemical
- Admixtures
- Surface Applied Corrosion Inhibitors
Products for Concrete Corrosion Prevention and Mitigation include:

Concrete Quality
- Admixtures
- Alternative Reinforcement

Steel applied Protection
- Coatings
- Active Primers

Surface applied Protection
- Coatings
- Impregnations

Concrete Replacement
- Repair Mortars
- Fairing Coats

Concrete Strengthening
- Fiber reinforced Coatings
- Pile Encapsulation

Electrochemical Protection
- Sacrificial Anodes
- Surface applied C. I.
Corrosion Control Technologies

- Prevention
- Protection
- Mitigation

Combination

- Alternative Reinforcement
- Admixture
- Corrosion Inhibitors
- Membranes & Coatings
- Rebar Coatings
- Penetrating Sealers
- Increased Cover
- SACI
- Embedment & Injection
- Corrosion Inhibitors
- Discrete Galvanic Anodes
- Cathodic Protection
  - Impressed Current
  - Distributed Galvanic Anodes
- Electrochemical Chloride Extraction
- Electrochemical Realkalization
Non-Corrosive Reinforcement

**PRO**
- Permanent
- Eliminates Corrosion

**CON**
- EXPENSIVE
- Design may be different
- Compatibility with conventional reinforcing?
- Pinholes on Epoxy Coated
- Bond on galvanized & epoxy & FRP

**Design phase**

**Stainless steel, FRP bar and specialty alloys**
- Stainless
- Galvanized

**Epoxy coated steel**
- Epoxy Coated Bar
- FRP

**Fiber reinforced polymer**
- Bar
- Fabric
- Sheet
Alternative Reinforcement Relative Costs

- Stainless
- FRP
- MMFX
- Galvanized
- Epoxy Coated
- Black Bar

http://www.fdot.gov/materials/structural/meetings/crrb/12_deployment.pdf
ACI Webinar D. Darwin Corrosion Protection Systems for Reinforcing Steel
Feb. 6, 2018
ACI Webinar D. Darwin Corrosion Protection Systems for Reinforcing Steel
Feb. 6, 2018
PRO
- Preventative
- Usage history
- Rebar Contact

CON
- May leach
- Dosage Verification
- Dispersion Verification
- Concentration Dependency
- Consumption during inhibition?
- Proprietary

Inorganic (Nitrite)
Fe^{2+} + OH^- + NO_2^- \rightarrow NO↑ + γFeOOH

Organic
Anode and Cathode effects
Coat steel & decrease permeability

Design phase
Admixtures

- Retarder
- Anti-bleed (VMA)
- Defoamer
- Shrinkage reducing
- Shrinkage compensation
- Plastic expansion
- Accelerator
- Corrosion inhibitor
- Dispersant
- Air entrainment
- Mineral admixture

WHAT
Cementitious Binder Types

- **OPC** = Ordinary Portland Cement, Blended, & Performance-Based Hydraulic Cement
- **HAC** = High Alumina Cement
- **AAP** = Alkali Activated Pozzolan
- **CSA** = Calcium Sulfoaluminate Cement
- Polymer Cement = Polymer (Latex) Modifier + binder
- **MagPhos** = Magnesium Ammonium Phosphate
- **Gypsum** = Calcium Sulfate
PRO
- Renewable
- Inexpensive
- Possible to Enhance Appearance

CON
- Consumable (coatings)
- Section thickness increase (cover)
- Load increase
- Defects may magnify issues
- Detail and Inspection Intensive

Design & Construction phase

Wall Coating Products
Structural Repair
Shotcrete
PRO

- Aesthetic Appearance
- Relatively Inexpensive
- Recoatable & Repairable

CON

- May Need Dry Substrate
- Surface Preparation
- Maintenance
- Abrasion & CTE
- Snow Removal
- Impermeable Trap Moisture

Deck Membrane Products
Resinous Flooring

Construction, Maintenance, Repair Phases
Barriers:

Paint  Any pigmented liquid, liquefiable, or mastic composition designed for application in a thin layer that is converted to an opaque solid film after application. Used for protection, decoration, identification, or other functional purposes (SSPC)

Coating  A liquid, liquefiable, or mastic composition that is converted to a solid protective, decorative, or functional adherent film after application as a thin layer (usually >5 mils dry) (SSPC)

Penetrating Sealer  A material that has the ability to penetrate and seal the surface to which it is applied to either prevent or delay the penetration of liquid or gaseous media (after ICRI/SSPC)

Membrane  A protective surface treatment with a thickness greater than 30 mils (0.75 mm) and less than 250 mils (6 mm) applied to the surface of concrete
### Reinforcement Coatings

**PRO**
- Field application
- Low cost
- Mature technology
- Some claim bonding agents

**CON**
- Pinholes & Under-bar
- Bond to Concrete Window?
- Continuity of Coating
- Hardening Depending on Environment
- Incipient Anode

**Repair Phase**

**Rebar/Corrosion Protection**
PRO

- Renewable
- Inexpensive
- No Appearance
- Easy to apply
- Hydrophobization

CON

- Consumable
- Maintenance
- Effectiveness Monitoring
- High Hydrostatic
- Crack Bridging
- Solvent?
- Overspray

Water Repellents
PRO
- Renewable
- Inexpensive
- No Appearance
- Easy to apply

CON
- Inhibition, not solving
- Effectiveness monitoring
- Penetration
- Residue
- Volatility
- Many technologies
- Life cycle
- Product compatibility

Maintenance & Repair Phases
**PRO**
- Point source or general protection
- Follow corrosion activity (i.e. RH-Temp)
- Effectiveness monitoring
- Ring / incipient anode
- Self powered

**CON**
- Consumable
- Passivation?
- Excavation
- Oxidation buildup

**Galvanic Anodes**

**PREVENTION**
- Electrochemical

**PROTECTION**

**MITIGATION**

“Hockey Pucks”
- Hydrogel
- Arc Spray
- Imbedded mesh
- Hybrid

**Construction & Repair Phases**
Example of NOT breaking the chain

Fixing one patch causes the surrounding concrete to act like an *incipient anode*. This is also called “Halo Effect” or “Ring Anode Effect”
Galvanic Anodes – How They Work

Host concrete, high chloride content

Repair Area, chloride-free

At the Cathode:
- Excess electrons are consumed in a series of reactions within the electrolyte
- No physical change in the structure of the steel takes place
- Corrosion does not occur at the cathode

At the Anode:
- Zinc dissolves into the electrolyte as positively charged ions
- Physical effects of corrosion seen here
- Metal loses mass and form

Electrolyte
ICCP Proven to Prevent
Usage History
Various Systems

Expensive
Design and maintenance critical
Reinforcement continuity
Anode acidification
May cause AAR
H₂ Generation?
Appearance?
Good Trade Practices

- DDAS with design
- Low W/CM
- Satisfactory Material Quality
- Enough Binder for Strength
- Consistency for Consolidation
- Enough Cover
- Sufficiently Cured…

Concrete Maintenance

- Verify
- Inspect
- Fix cracks
- Keep the Water Out!

Don’t Delay, Problems GROW

Keep the Water Out!

It’s not so much about letting it go as submitting to the inevitable
MISTAKES

It Could Be that the Purpose of Your Life Is Only to Serve as a Warning to Others.
Questions

THANK YOU!

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