TEXAS A&M ENGINEERING EXPERIMENT STATION

Commercial Metals

Galvabar is owned and manufactured by Commercial Metals Company.

Dr. Stephen Yeomans, University of New South Wales, Canberra, Australia

Dr. Frank Goodwin, International Zinc Association

Homero Castaneda Lopez, Ph.D., Texas A&M University

Mike Stroia, GalvaBar

8:30 AM – 8:50 AM	Registration and Orientation
8:50 AM – 9:00 AM	Introductions
9:00 AM – 9:50 AM	Galvanizing for Corrosion Protection of Rebar in Concrete Presented by: Dr. Stephen R Yeomans, University of New South Wales, Canberra, Australia
10:00 AM – 10:50 AM	The Advantages of Galvanized Reinforcement toward Achieving 100 Bridges Plus Years Service Life Cycle Cost Analysis Presented by: Sc.D. Frank E. Goodwin, IZA (International Zinc Association)
11:00 AM – 11:30 AM	Comprehensive Corrosion Performance Study for Materials used for Reinforced Concrete (RC) System and Elements Presented by: Homero Castaneda Lopez, Ph.D., Texas A&M University, College of Engineering
11:30 AM – 12:00 PM	The Future of Galvanized Rebar and Continuous Galvanized Product Innovations Presented by: Mike Stroia, GalvaBar
12:00 PM – 1:00 PM	Lunch
1:00 PM – 1:30 PM	TEES Corrosion Lab Tour
1:30 PM – 2:00 PM	Infrastructure Corrosion Concept Discussion

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Galvanizing for corrosion protection of rebar in concrete

Dr Stephen R Yeomans
University of New South Wales
Canberra, Australia

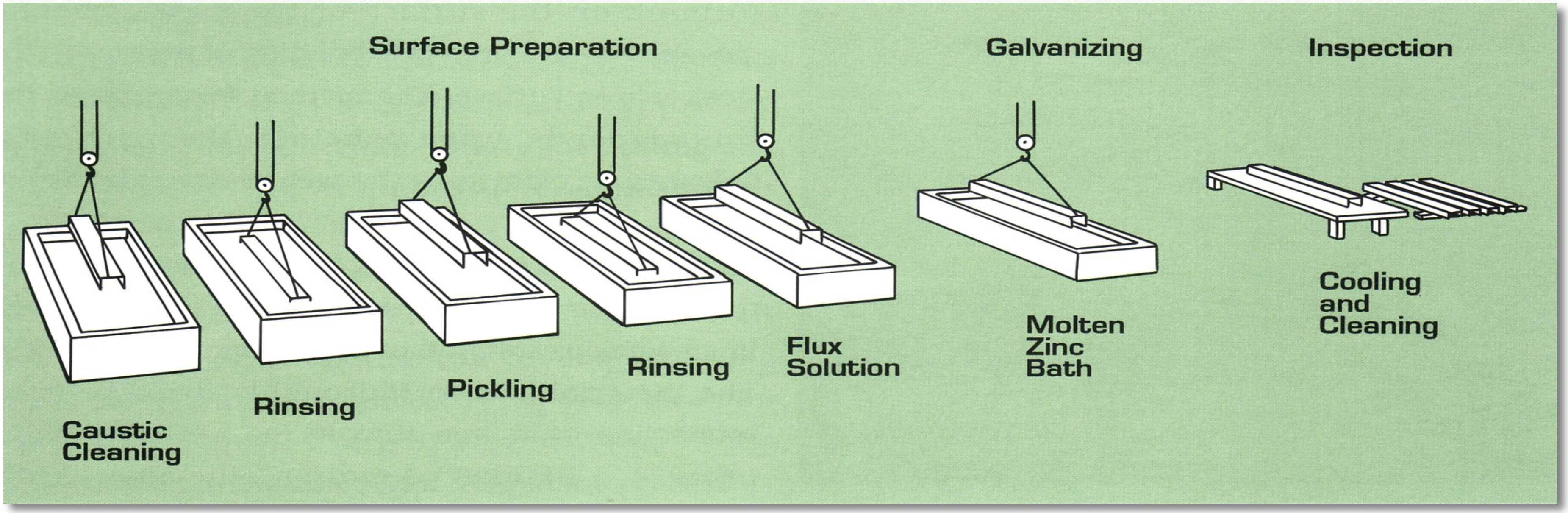
Hot Dip Galvanizing - HDG

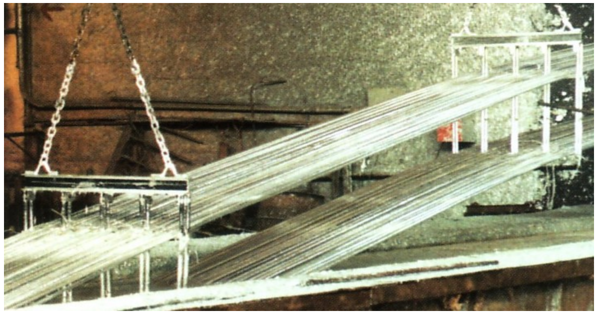
- Traditional batch coating process.
- Immersion in bath of molten zinc.

Continuous Galvanizing - CG

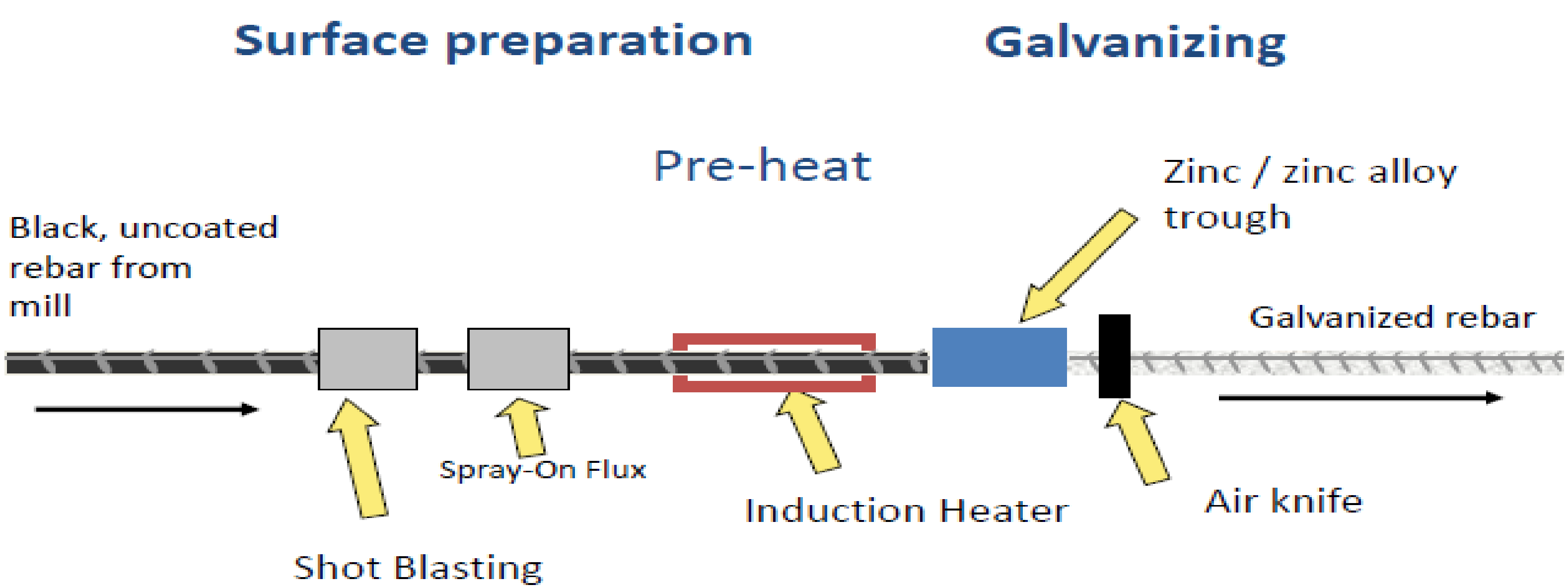
- Traditionally used for sheet, pipe and wire/rod.
- Implemented in US for reinforcing steel.

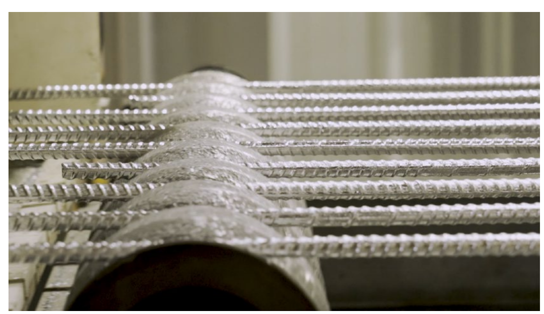
Hot Dip (Batch) Galvanizing - HDG





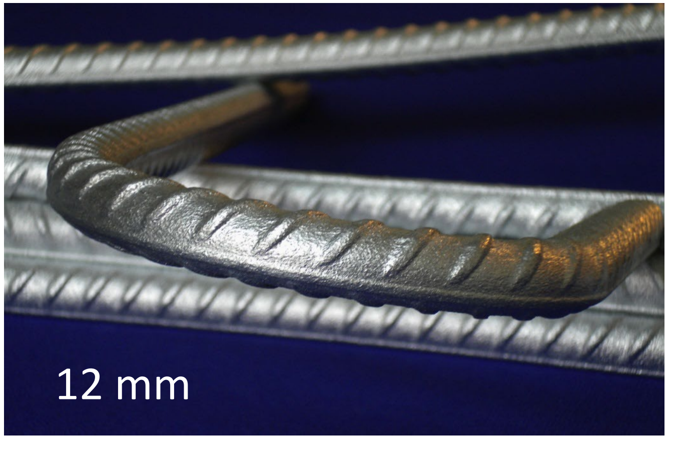
Continuous Galvanizing – CG





CGR Coating:

- Uniform thickness (~ 70 µ), circularity of coating
- Can use Si-containing reactive steels
- Formability – tight bend radii without cracking or peeling of coating.



ASTM A767 - Zinc-coated (galvanized) steel bars for concrete reinforcement

Class I: 1070 g/m^2 (150μ minimum)

Class II: 610 g/m^2 (86μ minimum)

ASTM A1094 - Continuous Hot-Dip Galvanized Steel Bars for Concrete Reinforcement

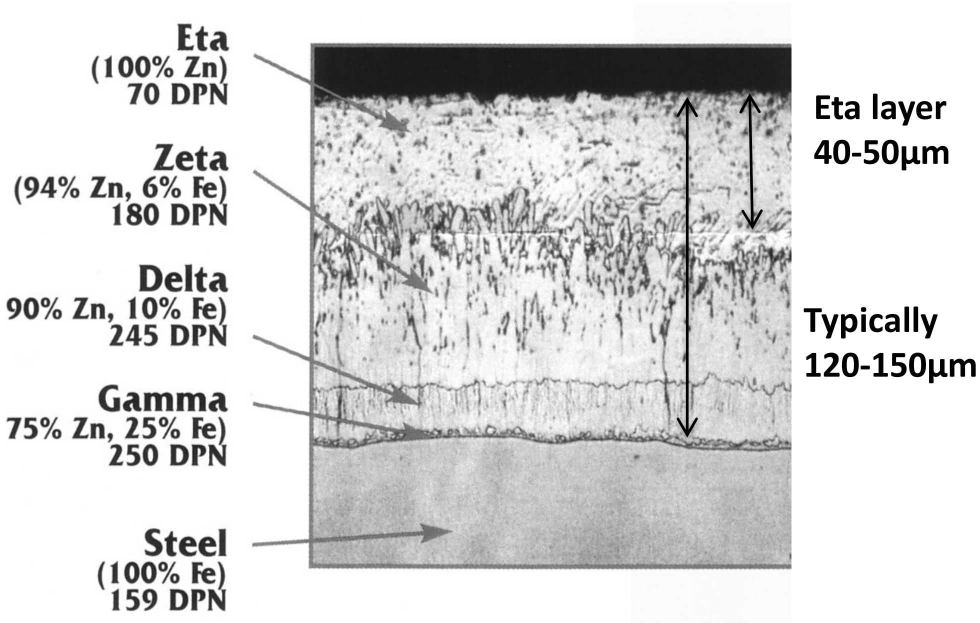
Coating mass minimum: 360 g/m^2 (50μ)

ASTM A1055 - Zinc and Epoxy Dual Coated Steel Reinforcing Bars

Sprayed zinc coating with flexible polymer coating.

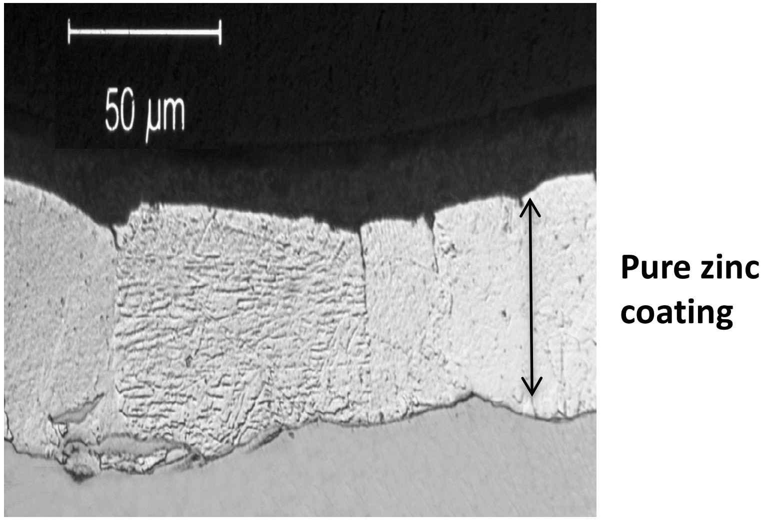
Hot Dip Galvanized

ASTM A767 - 85µm min.



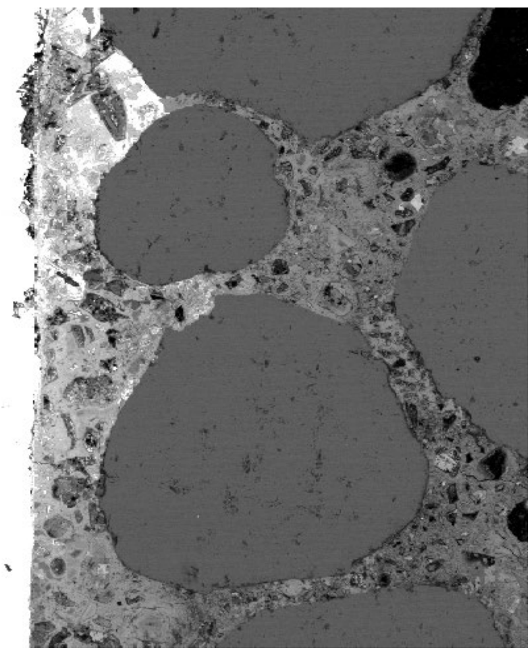
Continuously Galvanized

ASTM A1094 - 50µm min.

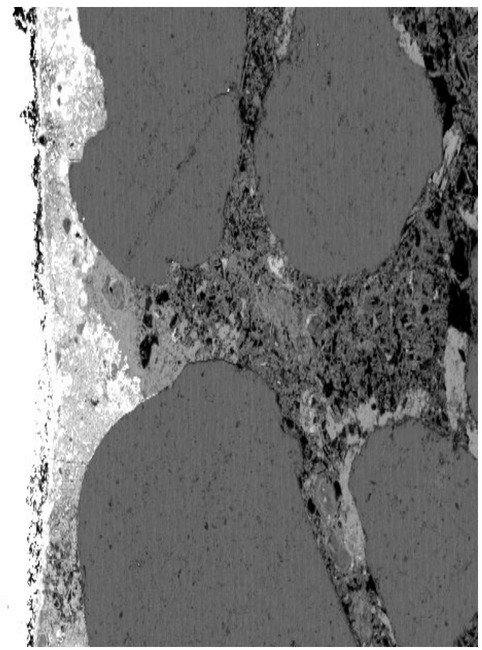


- Zinc passivates in wet cement: 2-10µm of pure zinc (eta) consumed.
- Forms dense and adhered layer of Calcium Hydroxyzincate (CHZ).
- Zinc corrosion products are friable and migrate into adjacent matrix.
- Densification of IFZ reduces permeability and chloride migration to bar.

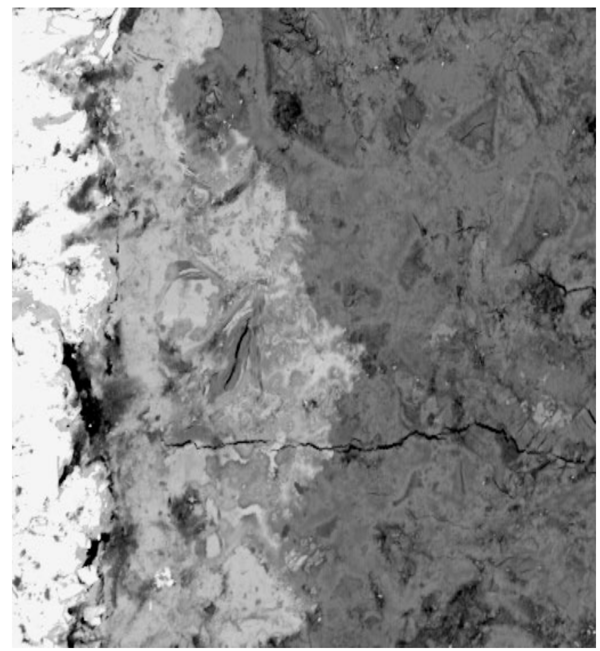
Migration of zinc products into cement matrix – less disruption to mass.



20x



50x



1000x

Zinc coating at left. Plume of ZnO corrosion products appear white against the gray, Ca-rich cement matrix.

Galvanized steel in concrete

- Coating provides barrier and sacrificial protection to steel.
- Pure zinc layer provides primary protection.
- Resists effects of carbonation to well below pH11.5.
- Significantly higher chloride tolerance than black steel:

  Chloride threshold at least 2.5x to 4-5x that of black steel.
- Ongoing corrosion protection in aggressive exposure:

  Significant life extension (50 - 100+ years) over black steel.

Design of galvanized structures

Galvanized reinforcement is direct replacement for black steel bar in all RC design and construction:

- no need for increased embedment lengths.

No separate design considerations apply.

No special concrete materials, mix requirements or site practices required.

Allows for design and construction simplicity.

Galvanizing of different steels

Early cold-twisted grades (410MPa):

– risk of embrittlement of double cold-worked material when galvanized;

– requires stress relief heat treatment.

Q and T or micro-alloyed grades (400-450MPa):

– satisfactorily galvanized without need for special processing requirements;

– no significant effect on strength or ductility.

Galvanized high-strength (500 MPa) rebar

Superior mechanical properties retained after galvanizing;

Slight improvement in yield/ultimate stress and ductility (due to mild stress relief).

Property	Effect of galvanizing
Tensile strength	No change from un-galvanized condition
Bending	No change from un-galvanized condition
Toughness	Similar to ungalvanized condition

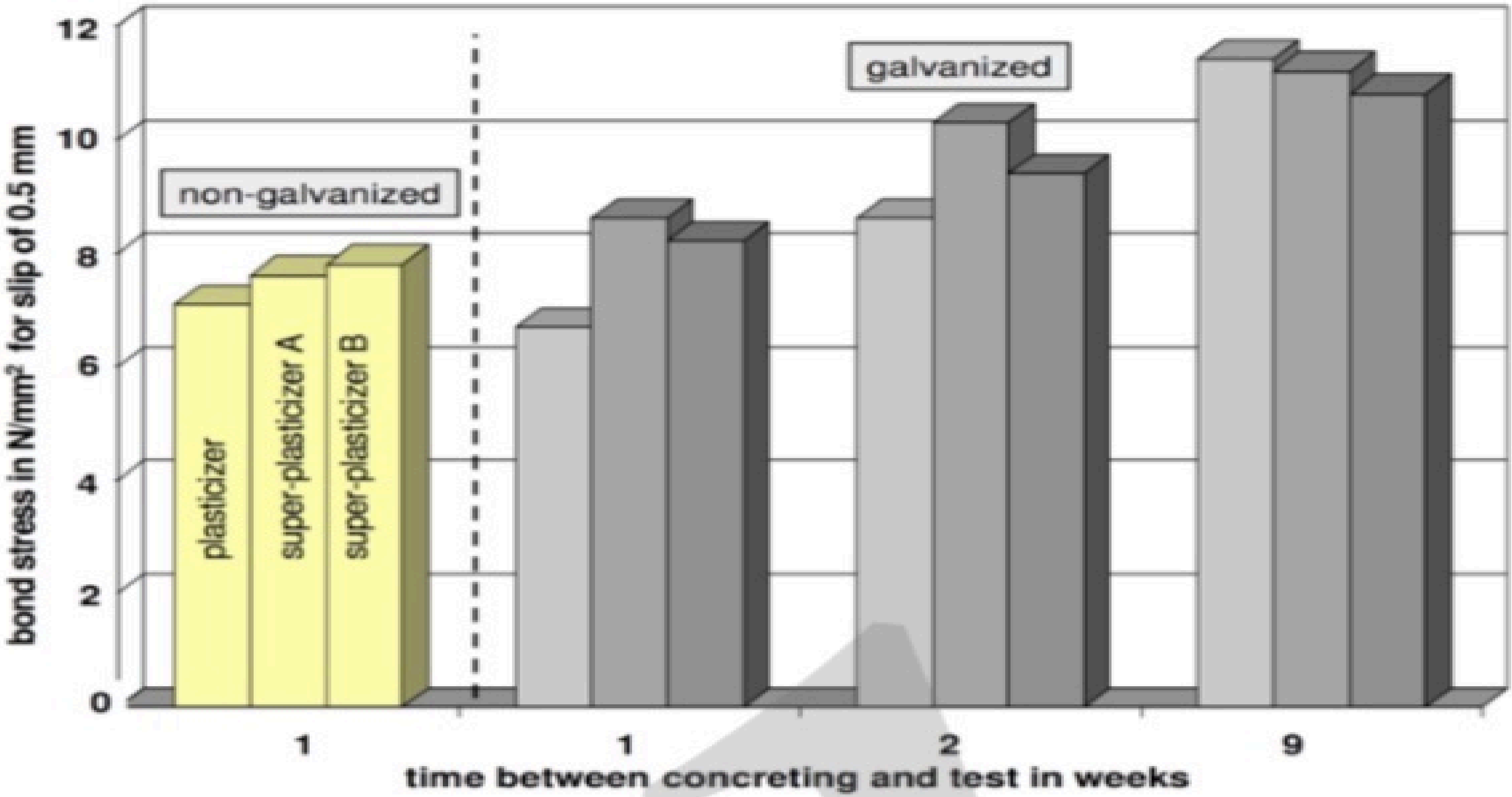
Bond of galvanized bar in concrete

Very strong adhesion between galvanized bar and concrete contributes significantly to bond.

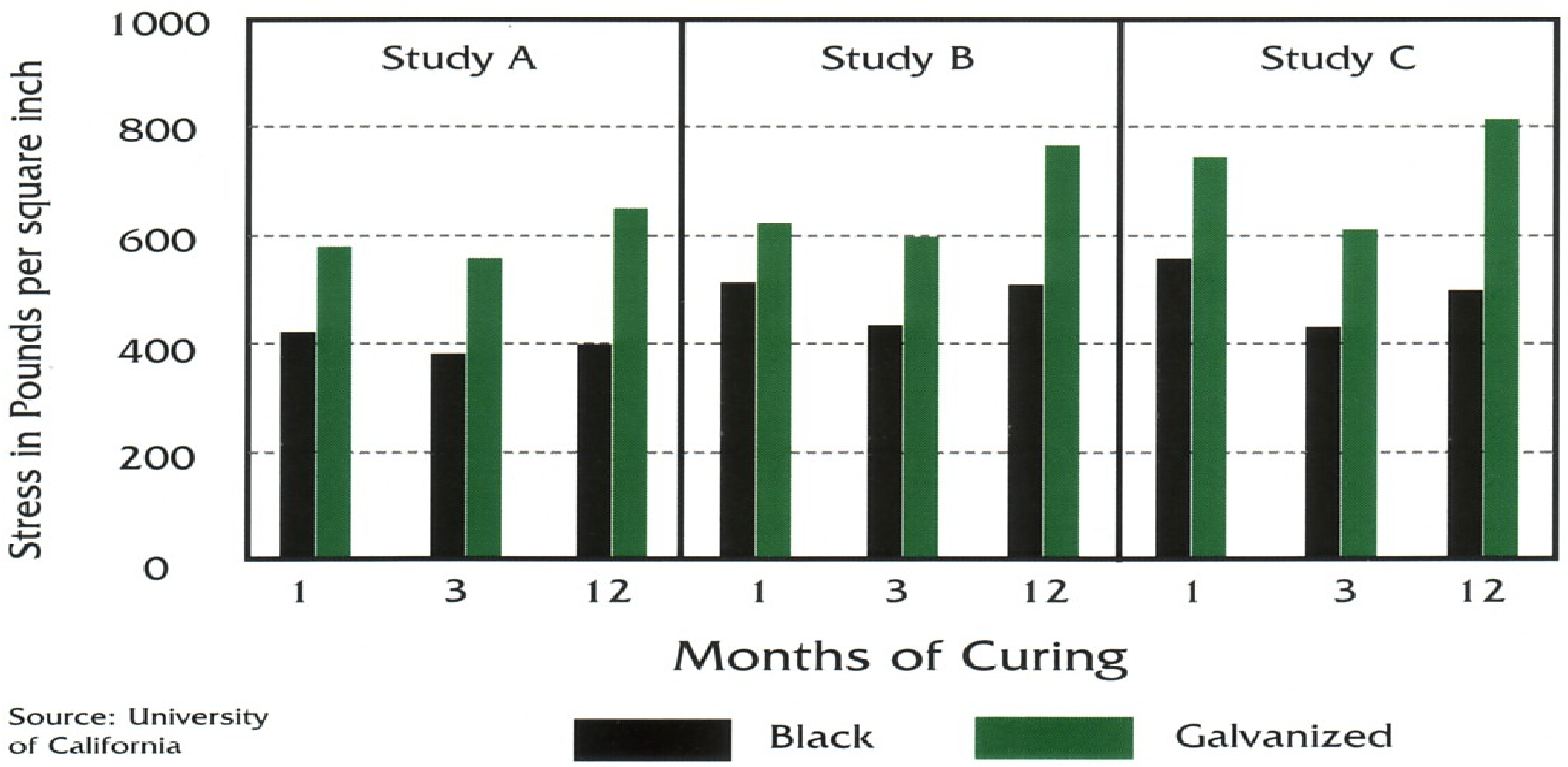
Bond strength of galvanized bar at 28 days not less than black bar (most often significantly higher).

Slip of galvanized bars under load is less that of equivalent black steel bars.

Bond strength development

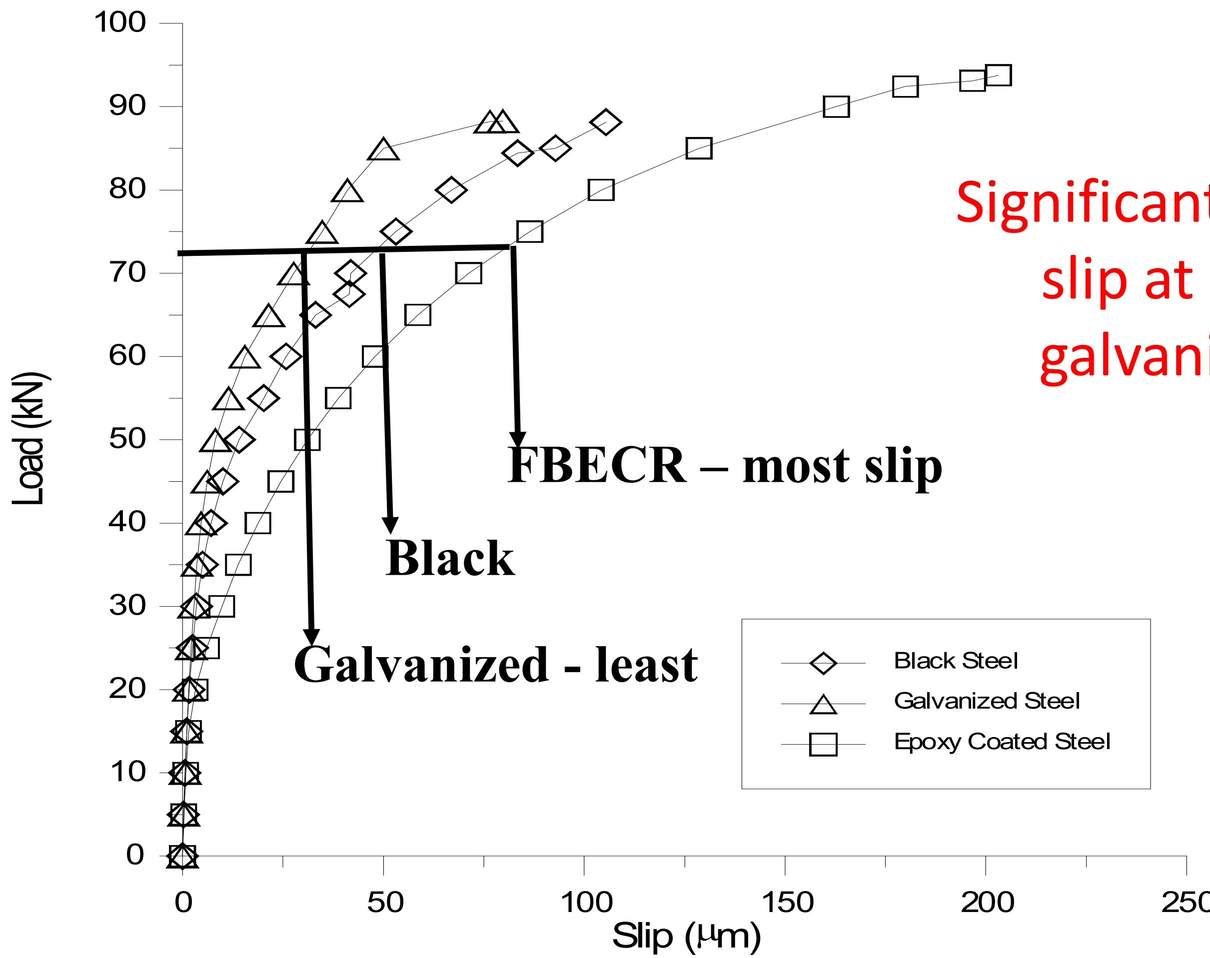


Superior bond of galvanized bar



Source: University of California

Load-slip data for ribbed bar



Significantly reduced slip at load for galvanized bar

Reference: Kayali & Yeomans 2000

Pullout testing per ASTM A994 1995 using beam-end test specimens

US Bridge survey data: 1975-2002

Location	Build	Inspect	Chlorides (kg/m^3)	Zinc coating (microns)
Boca Chica Bridge , FL	1972	1975	1.17	130
		1991	1.21	102
		1999	1.93	170
Tioga Bridge, PA	1974	1981	0.35	150
		1991	0.64	224
		2001	1.34	198
Curtis Road Bridge, MI	1976	2002	4.13	155
Spring Street Bridge, VT	1971	2002	2.50	191
Evanston Interchange, WY	1975	2002	1.53	236

Report: Residual zinc coating thicknesses indicates a further 40+ years of maintenance-free corrosion protection.

[ACI Chloride threshold 0.6 km/m^3; ASTM A767 - 85µ min thickness]

Boca Chica Bridge, Florida (1972)

1975

Zinc – 130 microns

Chlorides - 1.17 kg/m^3

1991

Zinc – 102 microns

Chlorides – 1.21 kg/m^3

1999

Zinc – 170 microns

Chlorides – 1.93 kg/m^3

Chloride levels at all inspections were well above the ACI threshold level (to 3.2x).

Tioga Bridge, Pennsylvania (1974)

1981

Zinc – 150 microns

Chlorides – 0.35 kg/m^3

1991

Zinc – 224 microns

Chlorides – 0.64 kg/m^3

2001

Zinc – 198 microns

Chlorides – 1.34 kg/m^3

Chloride levels at 1991 and 2001 above the ACI threshold level (to 2.2x).

Curtis Road Bridge, Michigan (1976)

2002 Inspection

Zinc – 155 microns

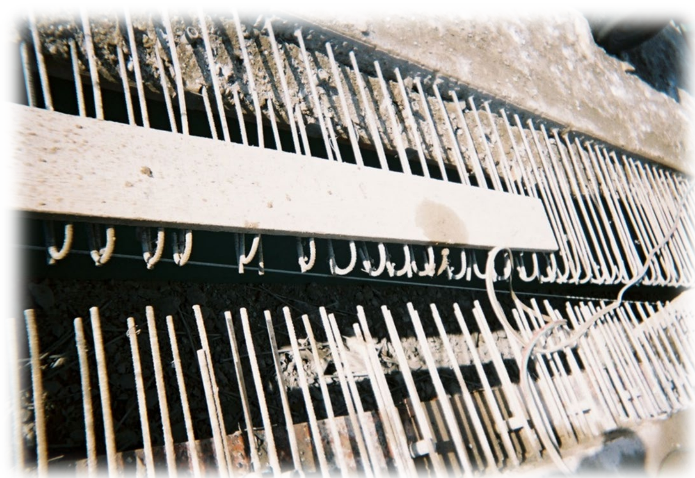
Chlorides – 4.13 kg/m^3

Chloride level at 2002 was 6.9x above ACI threshold level for black steel.

Route 66 bridge deck – 30 year case study

During maintenance for new crash barrier, original HDG deck reinforcement was uncovered. In excellent condition after 30 years and was re-cast into new barrier.

Chloride content at the bar was 3.0 kg/m^3 (5x ACI) and 247-270μ zinc remained on surface. No need for any refurbishment.



Bridge and highway applications - USA

Galvanized reinforced concrete road and bridge deck construction

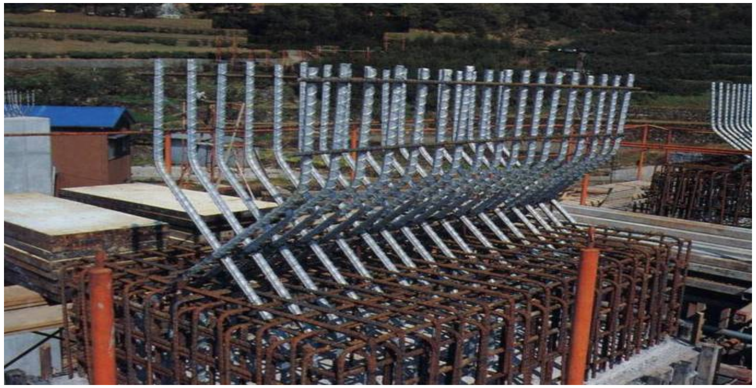
Bridge crash barriers

USA

Autoroute
40 France

Montreal
Canada

Bridge construction - Japan



Taipei-Linkou Bridge - Taiwan

1065m Linkou Bridge on northeast seafront coast of Taiwan.

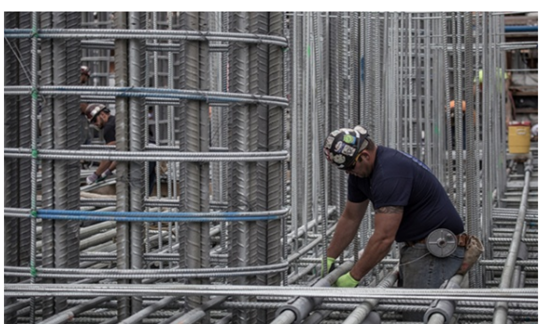
3000t of HDG rebar used for long-term protection in the salt-laden atmosphere of the Taiwan Strait.

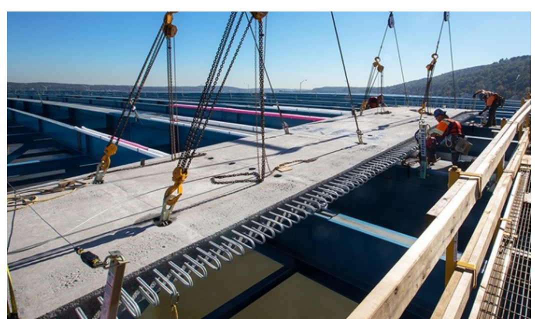
Bridge footings and columns

Typical construction using HDG reinforcement. Many such structures are in exposed coastal conditions with high salt content and humidity from prevailing on-shore winds and storms.

Mario Cuomo Bridge on Hudson River - designed for 100 year life (2018)

40,000t HDG rebar in 43 pairs of support piers, twin central towers, approach spans and abutments.





6000 HDG reinforced precast panels form the road deck.

Buffalo Creek Bridge, Iowa

75t CGR used in abutments, parapets and deck of new regional bridge.

Recent applications of CGR in balconies and seawalls in Southeast USA and Bermuda.

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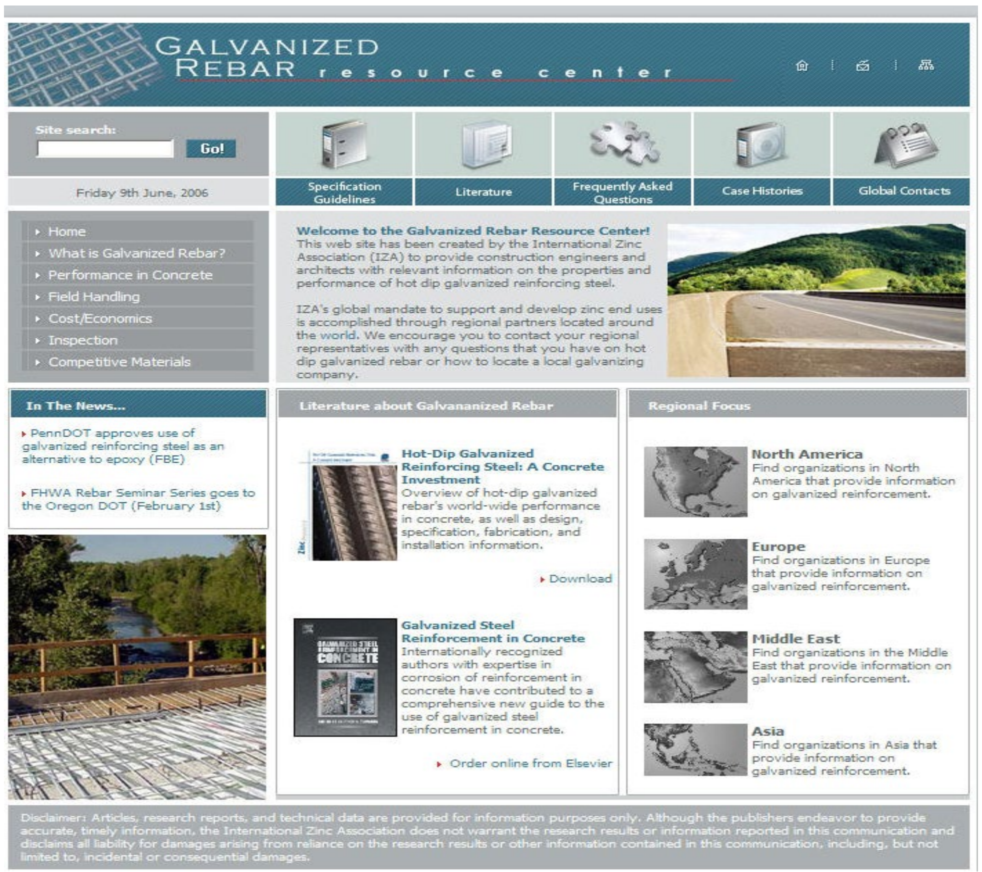
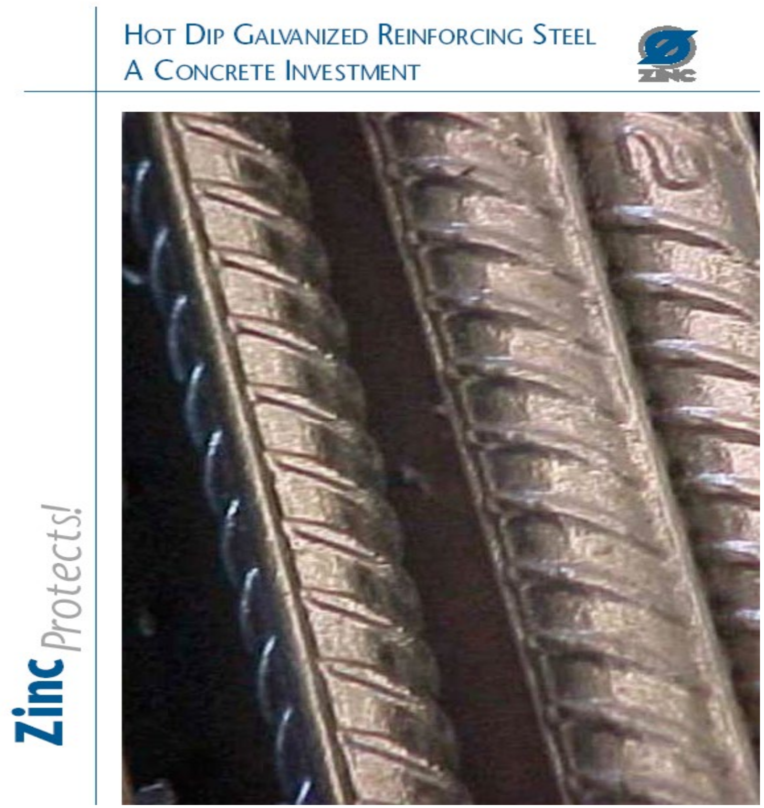
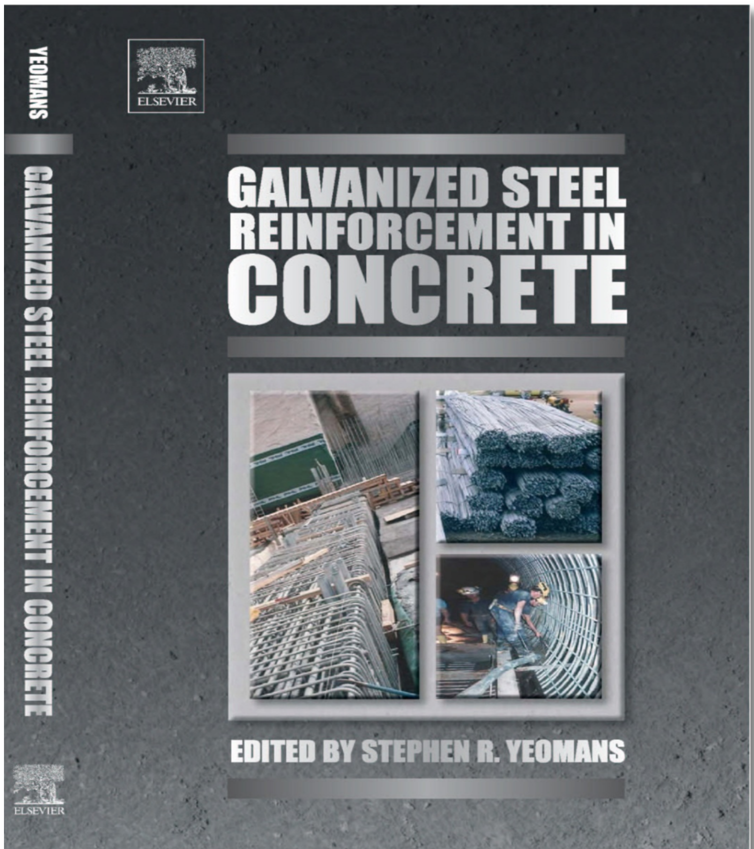
For further information:
www.galvanizedrebar.com





For a more detailed coverage…



ELSEVIER

SR Yeomans (Editor)
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The Advantages of Galvanized Reinforcement toward Achieving 100 Years of Service Life: Life Cycle Cost Analysis

Frank E. Goodwin Sc.D.
International Zinc Association
2019 TRAN-SET-CIR-AZZ Seminar
August 28, 2019

The Case of Virginia

- VDOT current requirements for steel reinforced concrete bridge decks are:
- concrete cover depth of 2.50 inches, minus zero, plus 0.50 inches,
- low permeable concrete with a maximum w/c = 0.45 and a minimum of 635 lbs of cementitious material, Portland cement plus flyash or slag cement, and
- corrosion resistant reinforcing steel.
- to achieve a minimum of 75 years of maintenance free service life for bridge decks in Virginia.

Modelling Service Life

- Most models are deterministic: but real life is not deterministic
- Prof. R. Weyers of Virginia Tech, under IZA sponsorship, used a full probability model to perform a Monte Carlo life cycle cost analysis.

LCC Model Limited to

- Steel reinforcing concrete bridge decks within the Commonwealth of Virginia;
- Bridge deck deicing salt exposure in Virginia Climate Zones, represented by three of the six zones in this state;
- VDOT low permeable bridge deck concrete;
- Zero, 3%, 6%, and 12% bridge initial surface cracking;
- Monte Carlo probability modeling based on Fick's Second Law of Diffusion;
- Reinforcing types: epoxy coated, galvanized and 316 LN stainless steel;
- Service life costs associated with maintaining bridge decks for a period of at least 75 years.

Fick’s Second Law of diffusion requires four input parameters:

(i) Surface chloride content which is influenced by the amount of deicing salt usage

(ii) Concrete cover depth which is controlled during the construction process

(iii) Chloride diffusion constant which is influenced by the type of concrete, construction methods, and environmental temperature and moisture conditions

(iv) The chloride corrosion initiation values which are influenced by the reinforcing steel type and surface conditions.

The six Virginia Climate Zones

Climate Zone		kg-Cl / lane-km (lb-Cl /lane-mile)
Southern Mountain (SM)	X	688(2,441)
Central Mountain (CM)		671(2,381)
Western Piedmont (WP)		220(781)
Northern (N)	X	4,369(15,501)
Eastern Piedmont (EP)		530(1,880)
Tidewater (TW)	X	225(798)

Salt usage depends both on climate and local traffic volumes

X = modelled in this study

What Cl^- values were used?

- Surface chloride values representing these three Climatic Zones were compiled from a Virginia bridge deck study which included 27 bridge decks built between 1984 and 1991 using a maximum w/c = 0.45
- Surface chlorides were acid soluble chloride determined from bridge deck cores and corrected for the amount of background chloride content. Thus, the figures representing only ingress chloride content.

Cl^- ranges used for the Monte Carlo study

- Northern, 17.0 to 9.4 kg/m^3 (28.7-15.8 lb/yd^3)
- Southern Mountains, 10.8 to 7.0 kg/m^3 (18.2-11.8 lb/yd^3)
- Tidewater Zone 9.7 to 3.0 kg/m^3 (16.4-5.0 lb/yd^3)

Cover Depths for Monte Carlo Simulation

- Seventy-five cover depths were used.
- The range, mean, and standard deviation were 44 to 76 mm, 62 mm, and 8.9 mm, respectively. (1.73-3.0”, 2.44” and 0.35”)
- The cover depth data set is a representative subset of cover depths for the Virginia construction era of 1984 to 1991.
- The same cover depth data set was used in all of the service life analyses.

Cl^- Diffusion Constant (1)

- For each low permeable concrete bridge deck core, background corrected acid soluble chloride content was determined as a function of depth.
- Chloride samples were taken directly over a reinforcing bar at 6 mm depths and thus accounted for the influence of the reinforcing bar on the rate of chloride diffusion into the concrete.
- The distribution of chloride concentrations as a function of depth was analyzed by fitting a one-dimensional solution of Fick's Second Law of Diffusion to determine the effective diffusion coefficient over the period that the deck has been in service

Cl^- Diffusion Constant (2)

- The bridge decks were built between 1984 and 1991 and core samples taken in 2005. Seventy five diffusion constants ranged from 1 to 60 mm^2/yr. The median was 5 mm^2/yr.
- This data set was used for all analyses within each Climatic Zone.

Effect of Surface Cracking on Diffusion Constant

- All of the bridge deck surface cracks do not extend to the depth of the reinforcing steel.
- There is no relationship between surface crack width and depth.
- Chloride samples were taken directly over the surface crack and followed the crack throughout its depth.
- Analysis showed the chloride ingress at surface cracks followed Fick's Second Law of Diffusion.
- Thirty-two diffusion constants were determined from cores with surface cracks. The range and median diffusion constant for crack condition were 6 to 1710 mm^2/yr and 61 mm^2/yr , respectively.
- The surface crack diffusion constant data set was shown to be statistically greater than the non-cracked condition.

More on Surface Cracking and Diffusion

- To account for the area influence of a surface crack, the length of the crack is multiplied by an influence length perpendicular and on each side of the crack by 50 mm.
- For the accessed conditions of 3%, 6%, and 12% cracked, non-crack diffusion constants were replaced with surface cracked diffusion constants.
- For the 3% crack condition, two non-crack diffusion constants were replaced, the smallest and largest values of non-crack diffusion constants were replaced by the smallest and largest crack diffusion constants. The two values represent 3% of the 75 non-crack diffusion constant data set values
- Likewise, five values were replaced for the 6% crack condition, two smallest, one median, and two largest. For the 12% crack condition nine values were replaced, three smallest, median, and largest values.

Cl^- Corrosion Initiation Concentration

- The most cited chloride corrosion initiation concentrations in plain steel reinforced concrete ranged between 0.59 to 0.88 kg/m^3 (kcm) (1 – 1.48 lb/yd^3) (pcy)
- These values were recognized as being lower conservative values. Subsequent research showed a large variability in the initiation values.
- However, the probability density function for chloride initiation of plain steel in concrete has not been generally agreed upon. Also, research studies using other than plain reinforcing steel often cite multiple values in comparison to plain steel.

Cl^- Corrosion Initiation Concentration for Black Rebar

- After much study of the literature and actual Virginia performance, settled on the range:

  0.39 to 2.6 kcm (0.66 to 4.4 pcy)

- The minimum, mode, and maximum for a triangular distribution is set at 0.39 kcm (0.66 pcy), 0.85 kcm (1.44 pcy), and 2.6 kcm (4.4 pcy) resulting in a distribution skewed to the lower values.

Cl^- Corrosion Initiation Concentration for Epoxy-Coated Rebar

- After much study of the literature and actual Virginia performance, settled on the same range as black rebar:

  The minimum, mode, and maximum for a triangular distribution are 0.39 kcm (0.66 pcy), 0.85 kcm (1.44 pcy), and 2.6 kcm (4.4 pcy)

- Epoxy-coated rebar merely lengthens the propagation period, from 5 years with black steel to 10 years with epoxy-coated rebar

Cl^- Corrosion Initiation Concentration for Galvanized Rebar (1)

Chloride Threshold	Method	Reference
At least 2.5 times black steel	In concrete, wet/dry cycle with NaCl	Yeomans, 1994
At least 2 to 2.5 times black steel	From laboratory and field studies	Yeomans, 2016
On average 1.58 times black steel	In concrete, wet/dry cycle-NaCl	Darwin, et. al. 2009
3.1 times black steel	In concrete, admixed with CaCl	Hegyi, et. al. 2015
1.5 to 2.5 times black steel	In chloride contaminated concrete	Bertolinli, et. al. 2013
2.0 times black steel	From laboratory and field studies	Sanchez, et. al. 2014

Cl^- Corrosion Initiation Concentration for Galvanized Rebar (2)

- We used the most cited value, 2.5 times the threshold of black bar for the time to corrosion initiation for hot-dipped galvanized reinforcing steel.
- The minimum, mode, and maximum for galvanized steel for this study was set at 0.97, 2.1 and 6.3 kcm (1.64, 3.5 and 10.7 pcy).

Corrosion Protection and Propagation (1)

- The corrosion protection time for galvanized reinforcing bar in Cl^- contaminated concrete is defined as the time period from corrosion initiation to dissolution of the Zn and Fe-Zn layers and thus the exposure of the underlying steel.
- Yeomans estimates this at 4 to 5 times black bar

Corrosion Protection and Propagation (2)

- For plain steel bar, the protection period is defined as the period from corrosion initiation to cracking and spalling of 50 mm (2”) of cover concrete, about 5 years
- For galvanized rebar, following the dissolution of Zn layers, corrosion of the underlying steel commences, but at an accelerated rate due to the higher Cl^- at the bar surface. The propagation period will be less than the 5 years for black bar, estimated at 2 years.
- Thus for hot-dipped galvanized steel in this study the protection period plus the propagation period is estimated at a conservative time period of 22 years.

Cl^- Corrosion Initiation Concentration for 316 Stainless (1)

Chloride Threshold	Method	Reference
>5 to > 8% by wt. of cement	Admixed in concrete or mortar	Hansson, 2016
3.5% by wt. of cement	Ponding of concrete	Hansson, 2016
3.5 to 8% by wt. of cement	Concrete structures in salt laden environments	Pietro, 2004
2.6 to 3.5% by wt. cementitious material	Ponding of mortar	Islam, 2013
12.1 kcm	Ponding of concrete	Clemena, 2002
8.3 to 12.8 kcm	Chloride into mortar, potential gradient	Trejo, 2004
10 times plain steel	Chloride ingress, concrete laboratory	Sanchez, et. al. 2014

Cl^- Corrosion Initiation Concentration for 316 Stainless (2)

- Minimum, mode and maximum values of 9.4, 13 and 18.8 kcm (16, 22 and 32 pcy) used. Mode of 13 kcm (22 pcy) is 3.5% of cementitious material.
- When corrosion does begin, the Cl concentration is high, so the propagation period is 15 years (shorter than galvanized)

Summary of Cl^- Initiation Values

Bar Type	Minimum kcm (pcy)	Maximum kcm (pcy)	Mode kcm (pcy)	Propagation yrs
Black Steel	0.39 (0.66)	2.6 (4.4)	0.85 (1.44)	5
ECR	0.39 (0.66)	2.6 (4.4)	0.85 (1.44)	10
Galvanized	0.97 (1.64)	6.3 (10.7)	2.1 (3.6)	22
316 LN SS	9.4 (16)	18.8 (32)	13 (22)	15

Display of Results

- Bridge decks with 0,3,6,12% initial surface crack coverages considered
- Time to 2,4,8,12% deterioration calculated
- 12% is the effective service life, at which point the bridge deck is replaced

Results – Tidewater Climate Zone

Damage	Epoxy-Coated Black Rebar (years)	Galvanized Rebar (years)	316L Stainless Rebar (years)
No Surface Cracking			
2%	44	>100	>100
4%	54		
8%	72		
12%, EFSL	88		
3% Surface Cracking			
2%	38	83	>100
4%	50	>100	
8%	69		
12%, EFSL	87		
6% Surface Cracking			
2%	11	31	>100
4%	38	95	
8%	62	>100	
12%, EFSL	80		
12% Surface Cracking			
2%	11	25	>100
4%	15	51	
8%	44	>100	
12%, EFSL	65		

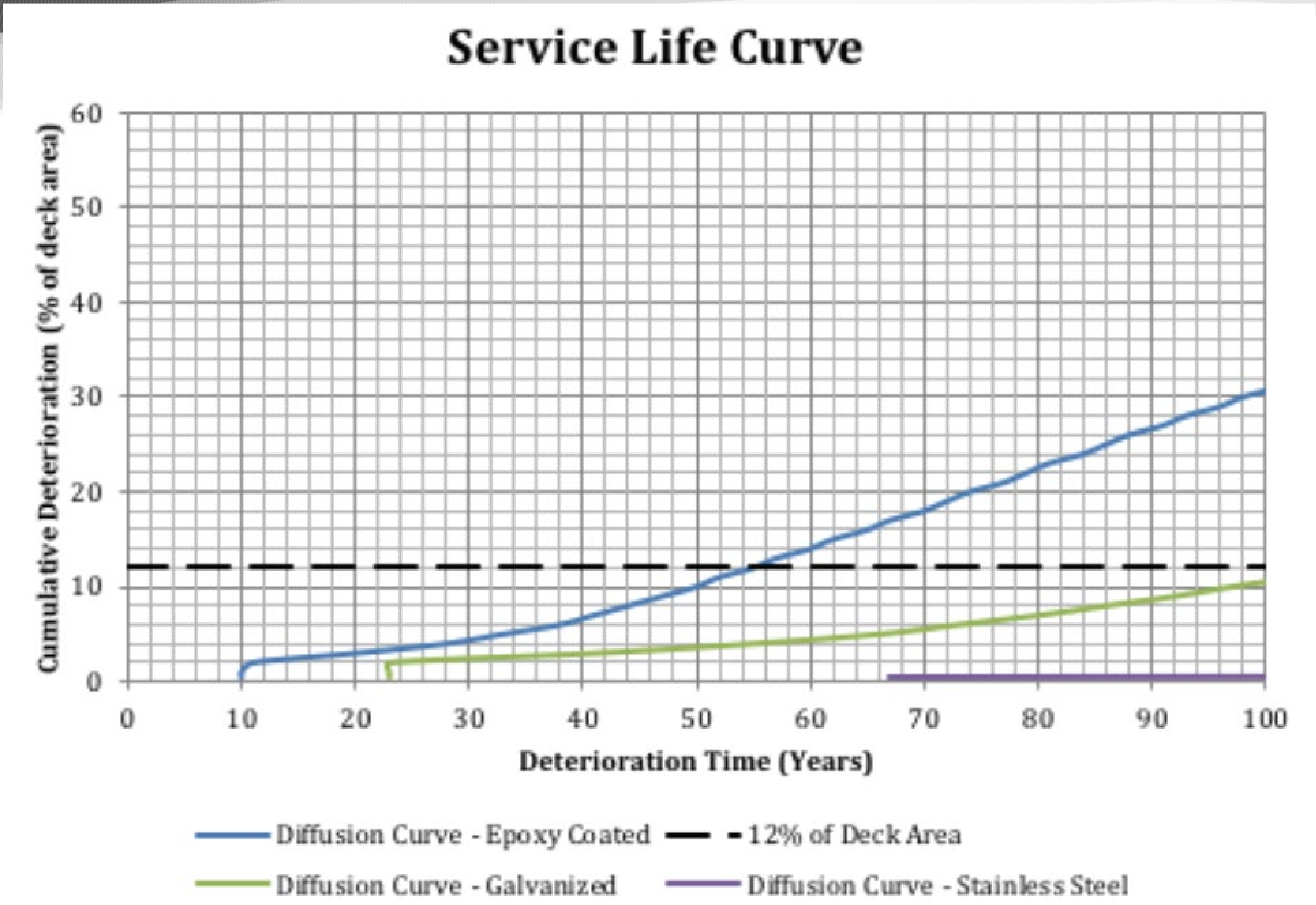
Results – Southern Mountains Climate Zone

Damage	Epoxy-Coated Black Rebar (years)	Galvanized Rebar (years)	316L Stainless Rebar (years)
No Surface Cracking			
2%	38	81	>100
4%	46	99	
8%	58	>100	
12%, EFSL	71		
3% Surface Cracking			
2%	34	68	>100
4%	44	92	
8%	58	>100	
12%, EFSL	71		
6% Surface Cracking			
2%	11	25	>100
4%	32	69	
8%	51	>100	
12%, EFSL	65		
12% Surface Cracking			
2%	11	24	>100
4%	17	36	
8%	37	85	
12%, EFSL	55	>100	

Results – Northern Climate Zone

Damage	Epoxy-Coated Black Rebar (years)	Galvanized Rebar (years)	316L Stainless Rebar (years)
No Surface Cracking			
2%	33	63	>100
4%	39	76	
8%	48	95	
12%, EFSL	59	>100	
3% Surface Cracking			
2%	29	55	>100
4%	37	71	
8%	49	96	
12%, EFSL	59	>100	
6% Surface Cracking			
2%	11	23	>100
4%	28	55	
8%	44	86	
12%, EFSL	54	>100	
12% Surface Cracking			
2%	11	23	>100
4%	15	31	
8%	30	62	
12%, EFSL	46	89	

Results – Northern Climate Zone



Cost Analysis

- Type B patching is defined as a removal depth to below the upper mat of reinforcing steel. The criteria used in this cost analysis for new/replacement decks are the factors determined previously for the three climatic zones, degree of surface cracking and EFSL at 12% deterioration.
- Twelve percent deterioration value was previously estimated during the SHRP Program (Weyers, 1993). For rigid overlays, in this case, latex modified concrete, very early strength (VDOT LMC-VE) is used. VDOT criteria were used for the LMC-VE overlay, 2% patching at 10 years and 2% patching every 2 years thereafter until 20 years with a presumed life of 25 years.

LCCA Method

- Life cycle cost analysis (LCCA) calculation used the Present Worth methodology as illustrated in the U.S. Department of Transportation Primer, 2002.
- The primer states “adjusting for inflation and discounting are entirely separate concerns, and they should not be confused by attempting to calculate both at once”.
- Nominal or market interest rates typically range between 3 to 5 percent. A real interest rate of 3.5% was used in the LCCA in this study.

Prices

Based on average deck thickness 8.5 in., 4,172 ft. of #5 bar plus 1,336 ft. of #4 bar/sf of deck surface, and average bridge deck of 40 ft. by 200 ft. (8000 sf).

Rebar Type	Epoxy-Coated Black Rebar	Galvanized Rebar	316L Stainless Rebar
	$239,670	$243,220	$331,080

In-Place LMC-VE,	$13.35/sf
Milling	$ 2.55/sf
Grooving	$ 0.60/sf
	$16.50/sf

Type B patching	$55.00/sf
Traffic Control	$1.70/sf

Cash Flow Requirements, Northern Zone, 6% deck initial surface cracking

Percent Deterioration	At Year	Activity	Cost $	Factor 3.5%	LCC $
Epoxy Coated Rebar, Initial Construction					239,670
2%	11	Patch	9,120	0.6849	6,250
4%	28	Patch	9,120	0.3816	3,480
8%	44	Patch	18,240	0.2201	4,010
12%	54	Overlay	145,600	0.156	22,720
2%	64	Patch	9,120	0.1106	1,010
4%	66	Patch	9,120	0.1032	940
6%	68	Patch	9,120	0.0963	880
8%	70	Patch	9,120	0.0899	820
10%	72	Patch	9,120	0.084	770
12%	74	Patch	9,120	0.0784	720
Total Costs			467,350		281,270
Galvanized Rebar, Initial Construction					243,220
2%	23	Patch	9,120	0.4533	4,130
4%	55	Patch	9,120	0.1508	1,370
6%	75	Patch	9,120	0.0757	690
Total Costs			270,580		249,410
Class III Stainless Rebar, Initial Construction			331,080		331,080

Present (Non-Discounted) Cost and Life Cycle Cost (LCC) for Northern Zone

Rebar Type	Present Cost $	Difference		LCC $	Difference	
		$	%		$	%
3% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	458,230	--	--	271,170	--	--
Galvanized Rebar	261,684	-196,500	-43	245,400	-25,770	-10
316L Stainless Rebar	331,080	-127,150	-28	331,080	+59,910	+22
6% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	467,350	--	--	281,270	--	--
Galvanized Rebar	270,580	-196,890	-42	249,410	-31,860	-11
316L Stainless Rebar	331,080	-136,390	-29	331,080	+49,810	+17
12% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	502,300	--	--	296,920	--	--
Galvanized Rebar	288,820	-213,480	-42	253,340	-43,580	-15
316L Stainless Rebar	331,080	-171,220	-34	331,080	+34,160	+12

Present (Non-Discounted) Cost and Life Cycle Cost (LCC) for Southern Mountain Zone

Rebar Type	Present Cost $	Difference		LCC $	Difference	
		$	%		$	%
3% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	294,390	--	--	248,080	--	--
Galvanized Rebar	252,340	-42,050	-14	244,095	-3,980	-2
316L Stainless Rebar	331,080	+36,690	+12	331,080	+83,000	+33
6% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	312,630	--	--	258,180	--	--
Galvanized Rebar	263,740	-48,890	-16	248,100	-10,080	-4
316L Stainless Rebar	331,080	+18,450	+6	331,080	+72,900	+28
12% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	476,480	--	--	287,330	--	--
Galvanized Rebar	275,140	-201,340	-42	249,240	-38,090	-13
316L Stainless Rebar	331,080	-145,400	-30	331,080	+47,750	+15

Present (Non-Discounted) Cost and Life Cycle Cost (LCC) for Tidewater Zone

Rebar Type	Present Cost $	Difference		LCC $	Difference	
		$	%		$	%
3% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	267,030	--	--	244,620	--	--
Galvanized Rebar	243,220	-23,810	-9	243,220	-1,440	-1
316L Stainless Rebar	331,080	+64,050	+24	331,080	+85,720	+35
6% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	276,150	--	--	258,180	--	--
Galvanized Rebar	252,340	-23,810	-9	246,360	-4,190	-2
316L Stainless Rebar	331,080	+54,930	+20	331,080	+80,530	+32
12% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	294,390	--	--	257,330	--	--
Galvanized Rebar	261,570	-32,820	-11	248,790	-8,540	-3
316L Stainless Rebar	331,080	+36,690	+12	331,080	+73,750	+29

Conclusions

- For the bridge type considered in this study, with low-permeability concrete, a design cover depth of 2.5” (6.4 cm) and the ranges of chloride surface concentrations, galvanized reinforcing steel has the lowest cost of ownership for all combinations of deck cracking and environmental climate zones.
- The stainless steel is the most expensive choice based on life-cycle costs but does present a maintenance-free condition for service lives greater than the design life of a 100-year bridge.
- Epoxy-coated steel requires the greatest amount of maintenance over this service period and always has a higher life cycle cost (total cost of ownership) than galvanized rebar.

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Phase I- Comprehensive corrosion performance study for materials used for reinforced concrete (RC) system/elements

Yenny Cubides, Ivan Karayan, Homero Castaneda
Department of Material Science and Engineering, Texas A&M University

Background

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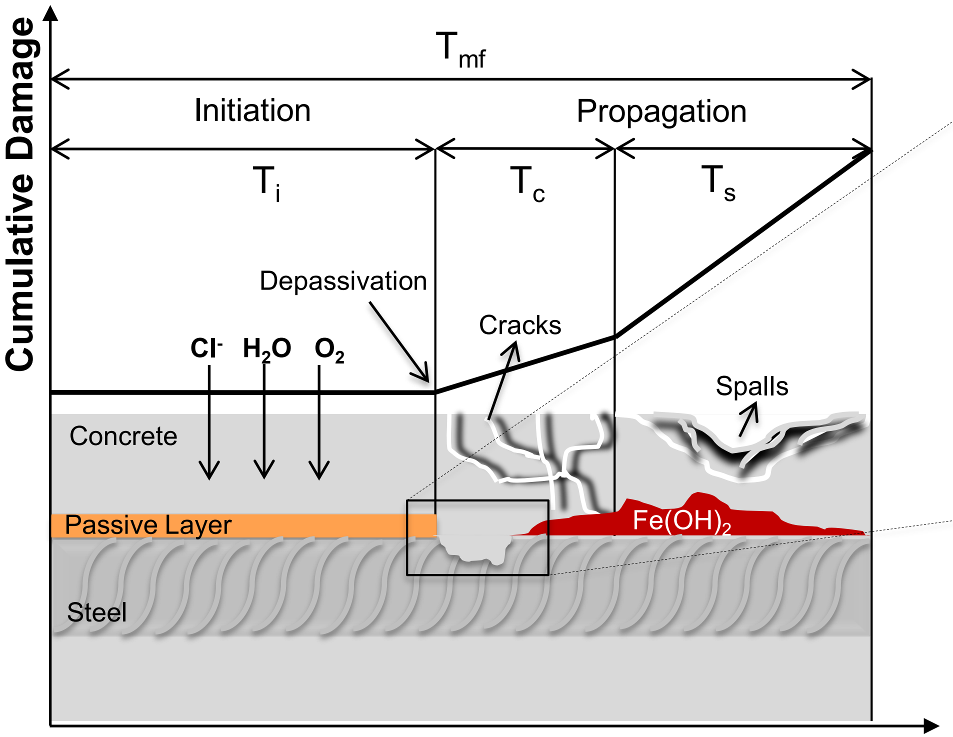
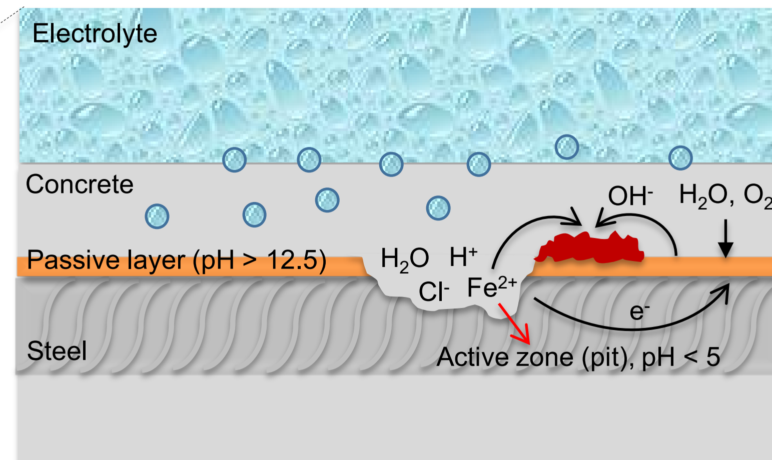
Corrosion Mechanism in Reinforced Concrete

Initiation and propagation periods for corrosion in reinforced concrete



T_i : Initiation Time
T_c : Time for appearance of cracking
T_s : Time for development of spalls
T_{mf} : Maintenance-Free Service Life

Localized attack (pitting corrosion) of reinforcing steel in concrete



Anode (active zone)

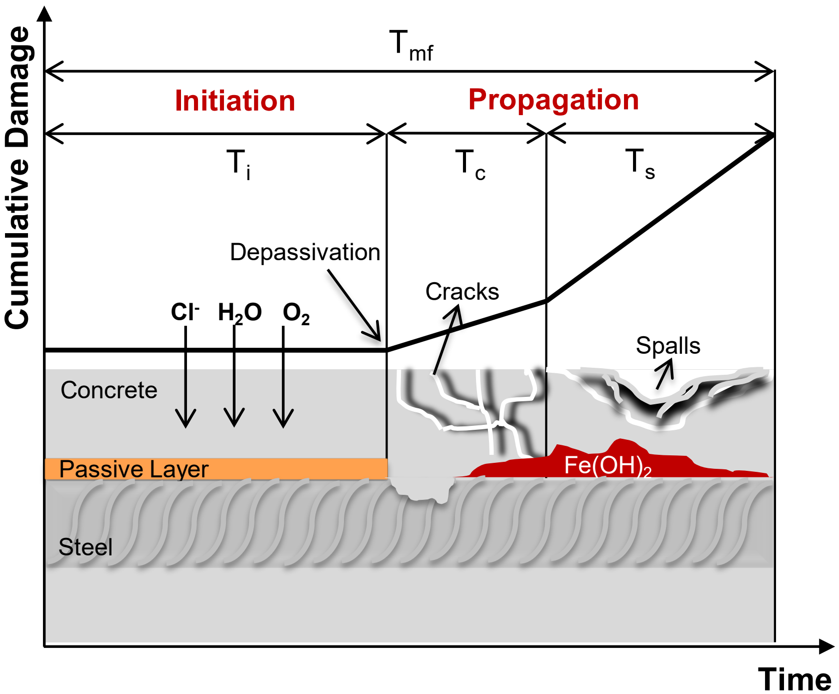
$$Fe \rightarrow Fe^{2+} + 2e^-$$
$$Fe^{2+} + 2Cl^- \rightarrow FeCl_2$$
$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2H^+ + 2Cl^-$$

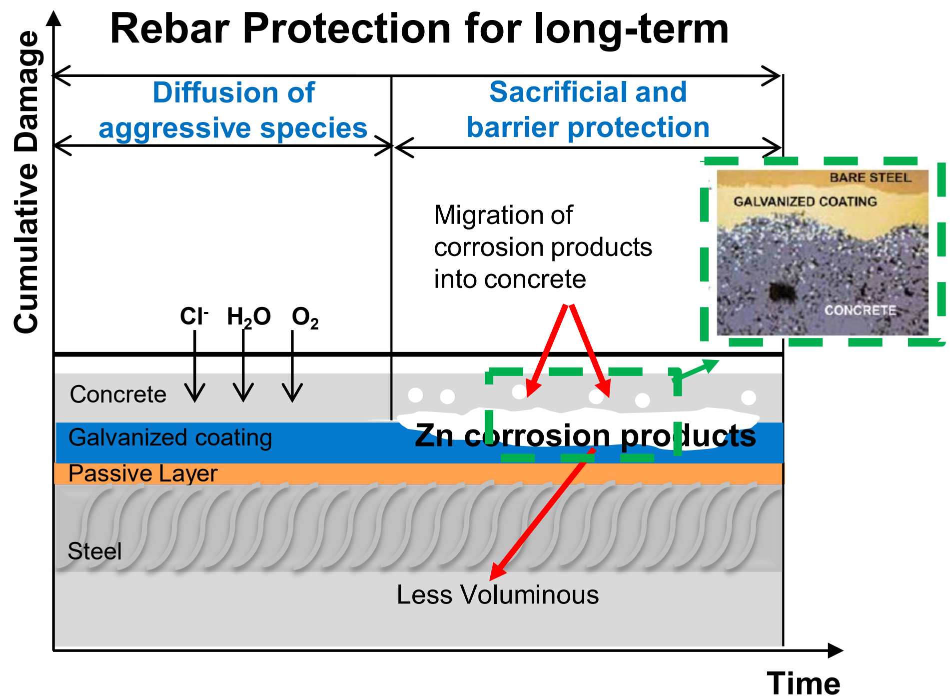
Cathode (passive layer)

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$$

Hypothesis

Corrosion Protection using Galvanized Coatings





Background

Coatings for Corrosion Protection

Protective coatings have been recognized as one of the most effective methods to protect reinforced concrete from corrosion

Coatings provide protection by:

- **Barrier Protection**
  - Fusion Bonded Epoxy
- **Cathodic and Barrier Protection**
  - Galvanized Steel

Objectives

Current Progress

- Conducting laboratory steady state aging conditions on different rebar materials used for reinforced concrete.
- Conducting laboratory accelerating testing conditions on different rebar materials used for reinforced concrete.
- Conducting laboratory testing conditions on RC samples.
- Conducting simulation of cycling harsh environment existed in the salt belt conditions (as unique and practical case in the USA).
- Conducting theoretical modeling based on dissolution mechanism and failures due to corrosion process and set up the basis for reliability modeling.

Materials

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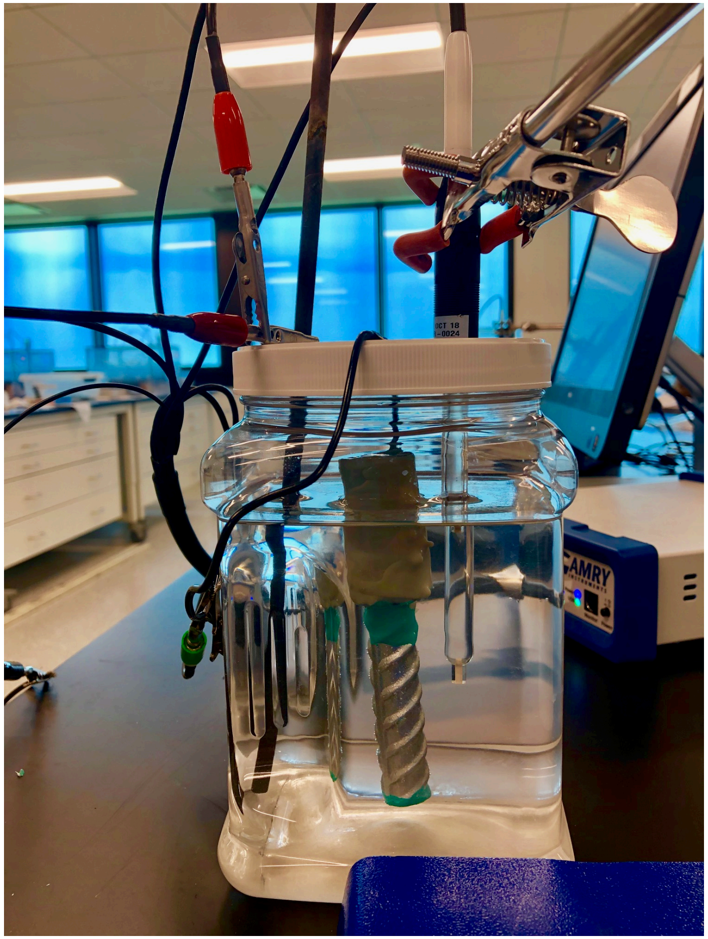
PHASE I

- 615 Control (Bare Carbon Steel)
- 1094 CGR (Continuous Galvanized Reinforced Rebar)
- 1094S CGR Smooth
- 1055 Dual-Coat (CGR + Epoxy)
- 767 Galvanized Steel
- 1035 Dual-Coat (MMFX steel + CGR)
  - 1035 (2)
  - 1035 (4)
  - 1035 (9)
  - 1035 (T)

MMFX – Martensitic Microcomposite Formable Steel

Corrosive Environments

Continuous Salt Immersion Test



- Electrolyte: Concrete Pore Solution: (0.08 M KOH, 0.02 M NaOH, 0.001 M $Ca(OH)_2$, 0.5 M NaCl)
- pH~12-13
- Immersion Time: 30 days
- Electrochemical Testing:
  - OCP: 10 min
  - EIS (100 kHz-10 mHz)
- Three-electrode Cell Configuration:
  - Reference: Saturated Calomel Electrode (SCE)
  - Counter: Graphite
  - Working: Rebar samples

Corrosive Environments

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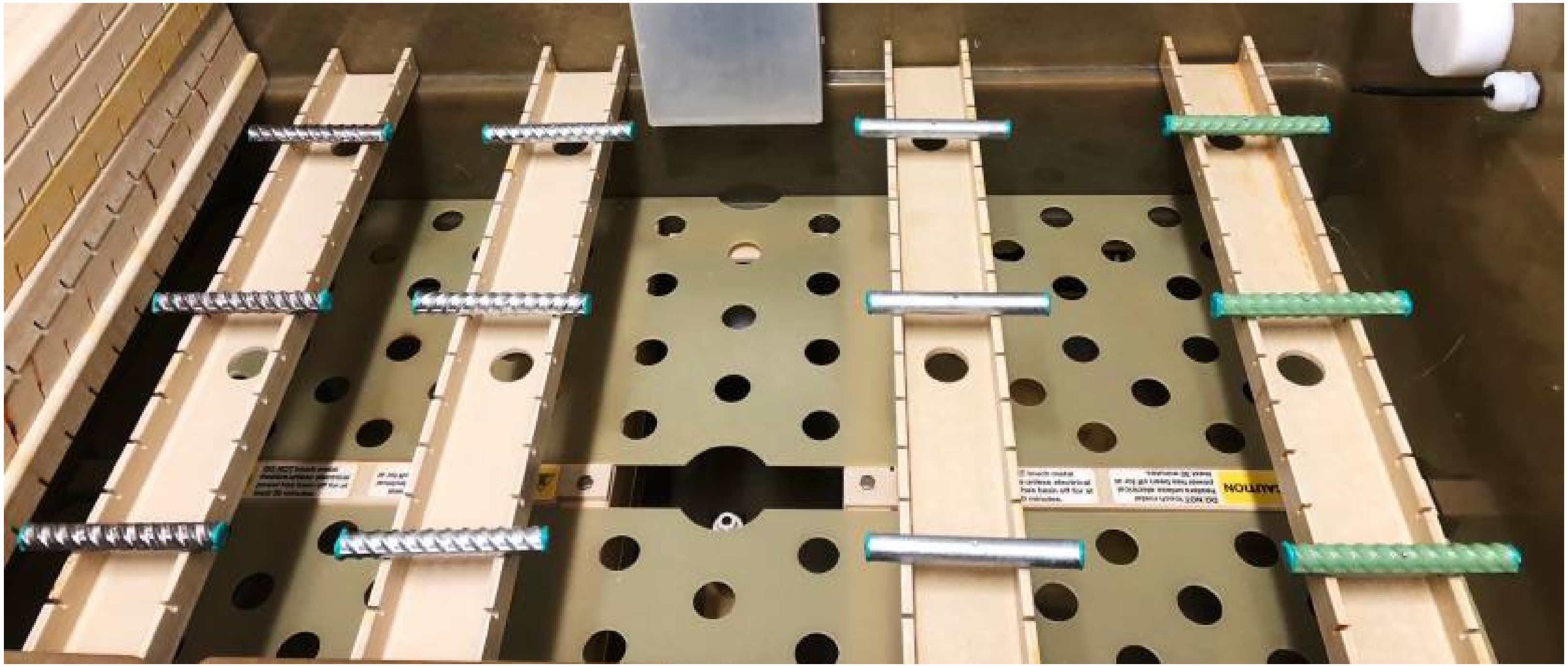
Cyclic Fog Chamber Test

- Cyclic Duration: 48 h wet / 48h dry for 7 cycles (28 days)
- Electrolyte: 5 wt.% NaCl
- Temperature: 35°C

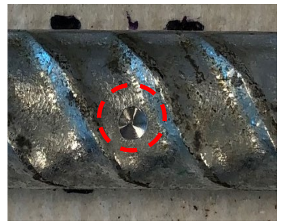


Corrosive Environments

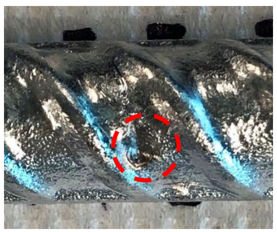
Cyclic Fog Chamber Test

615

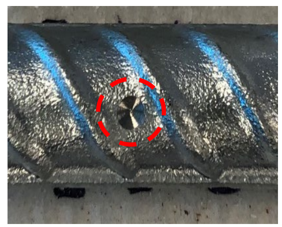
767



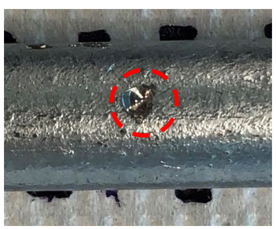
1094 CGR



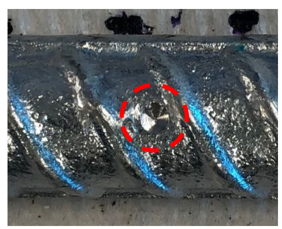
1035 (2)



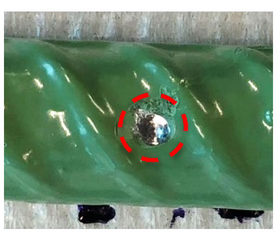
1094S



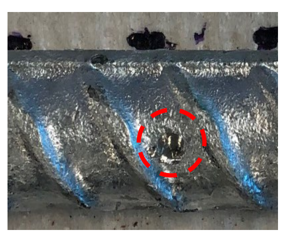
1035 (4)



1055

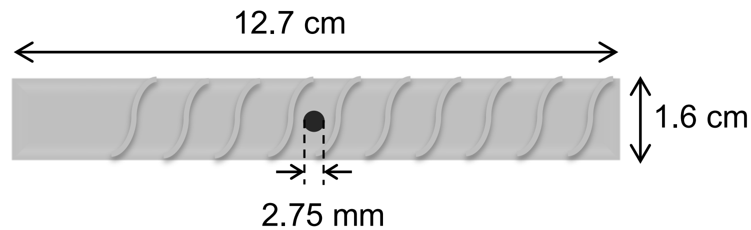


1035 (9)



1035 (T)

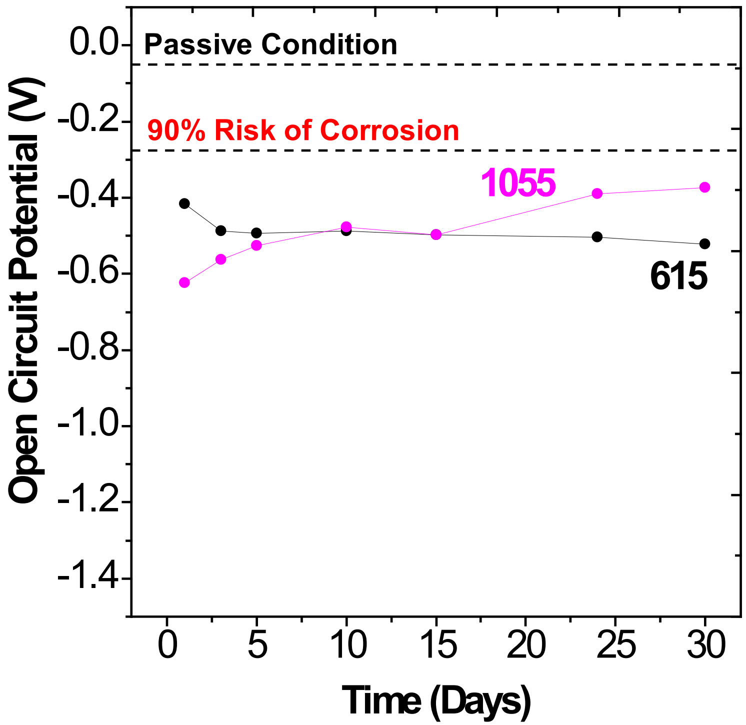
Rebar dimensions

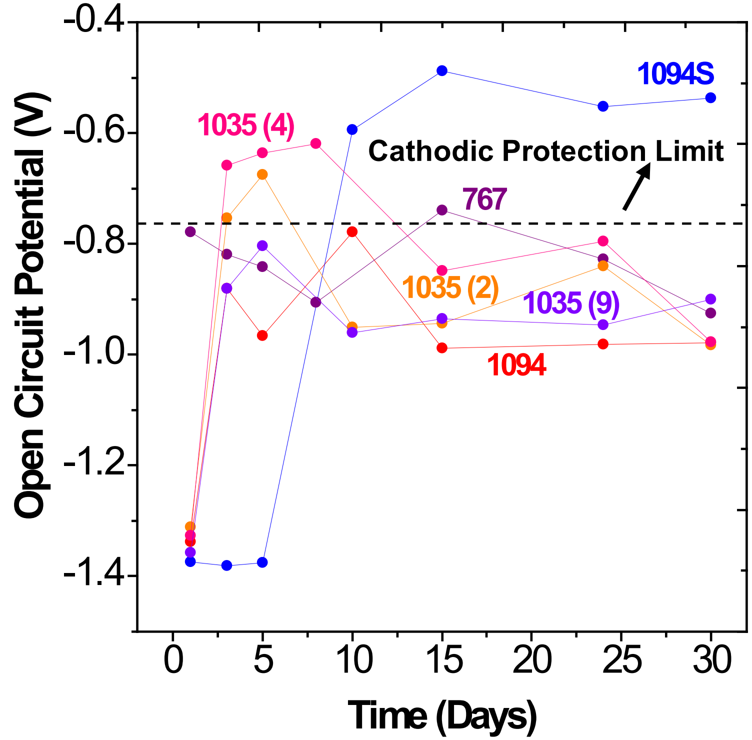


Rebar samples were drilled with a 1/8" bit for 1 mm of penetration

Continuous Immersion Test

OCP Results





The majority of the different coatings (except the 1055 Epoxy coating) provided sacrificial protection to the carbon steel rebar

Continuous Immersion Test

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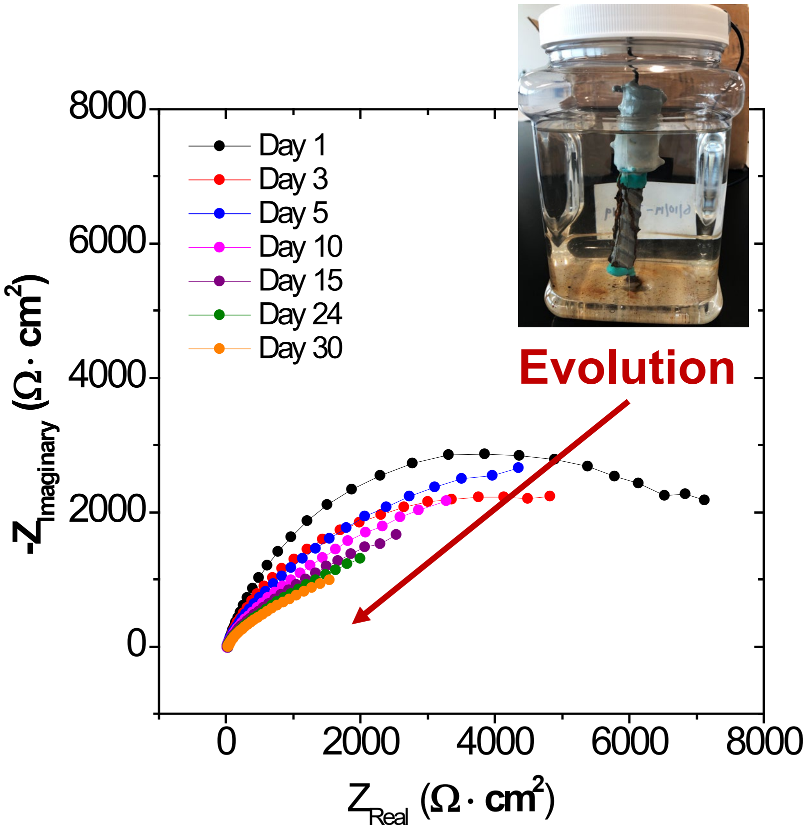
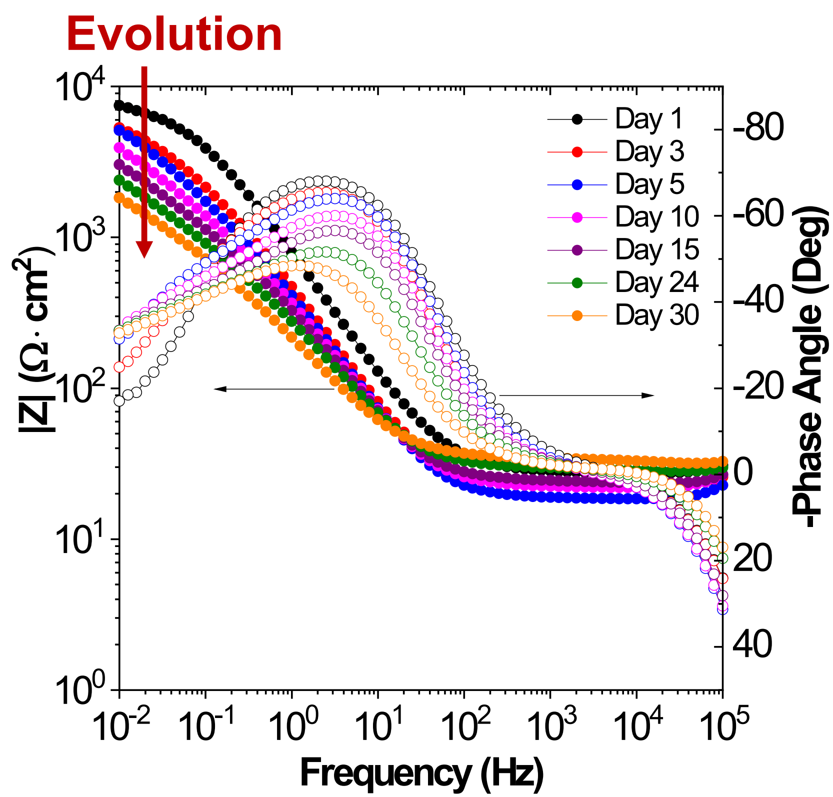
EIS Results for 615 Control Sample





The impedance gradually decrease overtime suggesting a continuous degradation of the carbon steel substrate

Continuous Immersion Test

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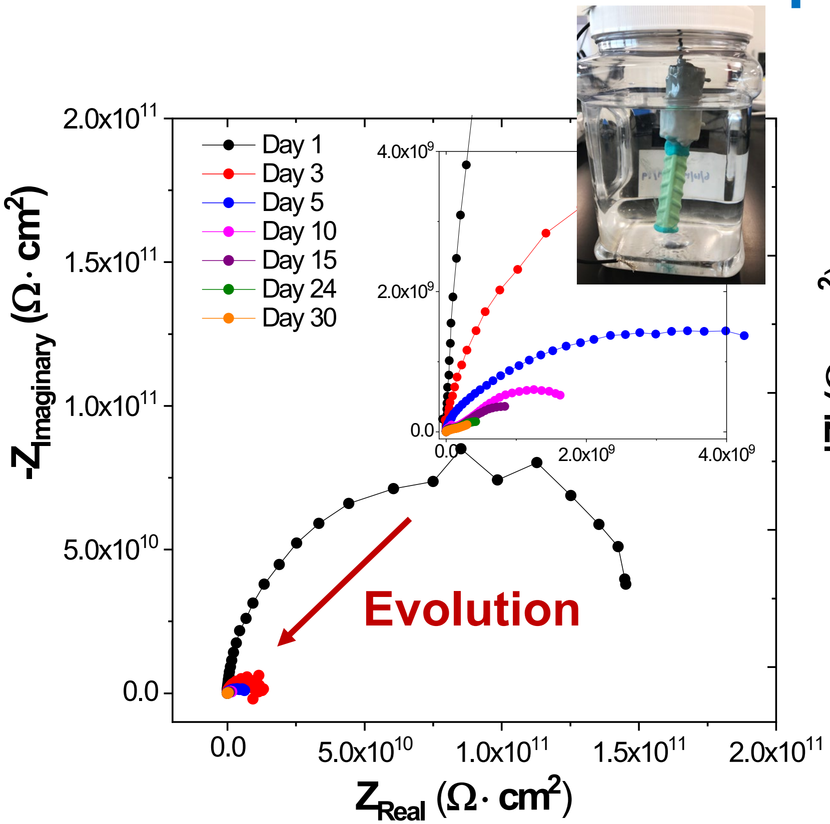
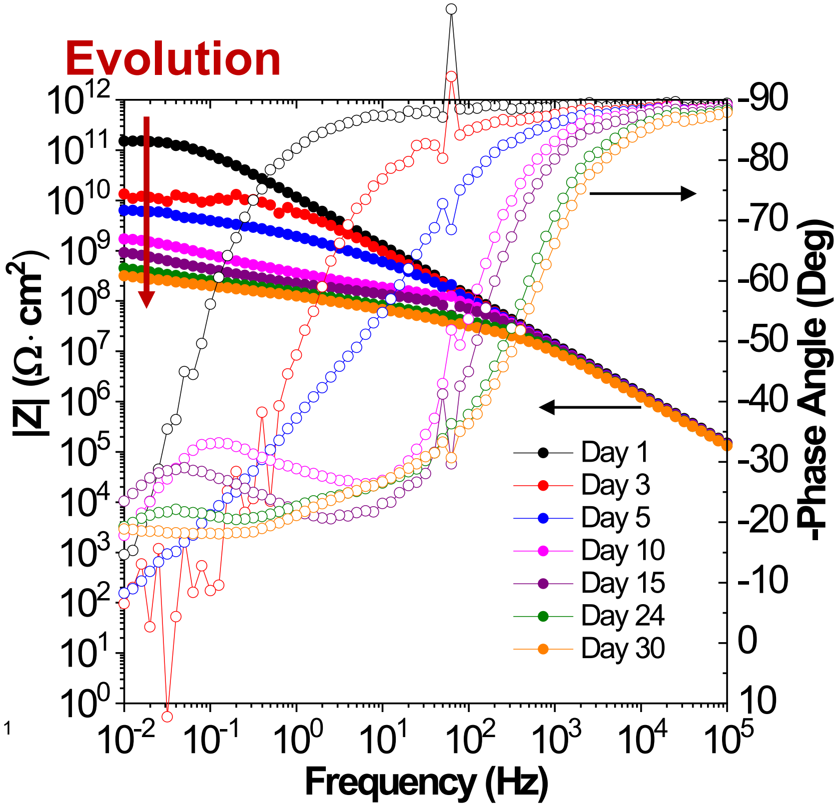
EIS Results for 1055 Sample





High impedance values due to excellent barrier protection, however impedance decreased overtime as a result of water penetration and initiation of corrosion processes at the carbon steel substrate (presence of a second time constant after 10 days of immersion)

Continuous Immersion Test

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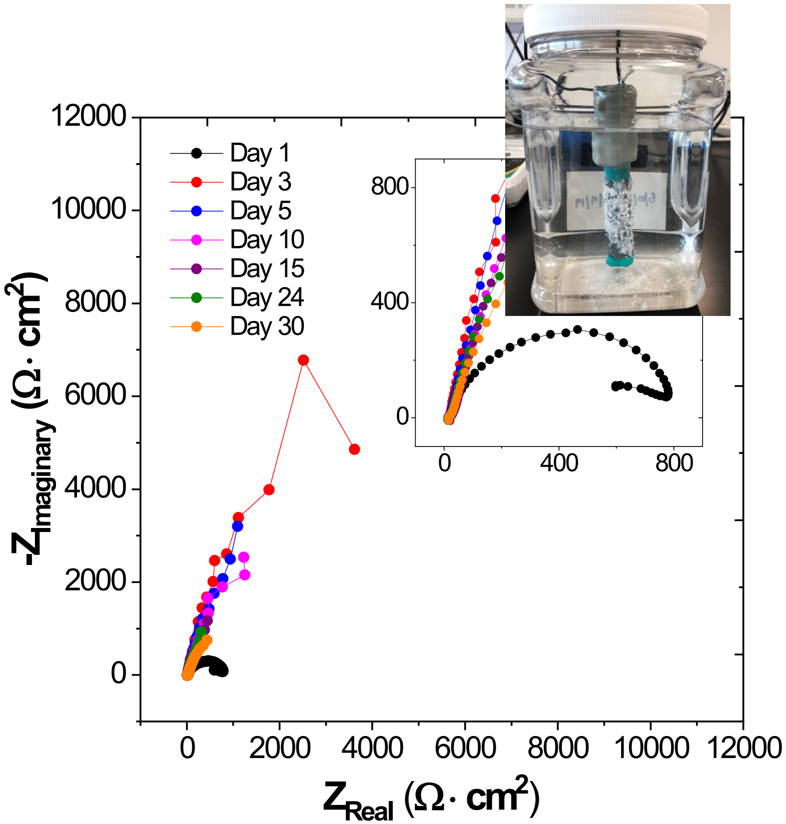
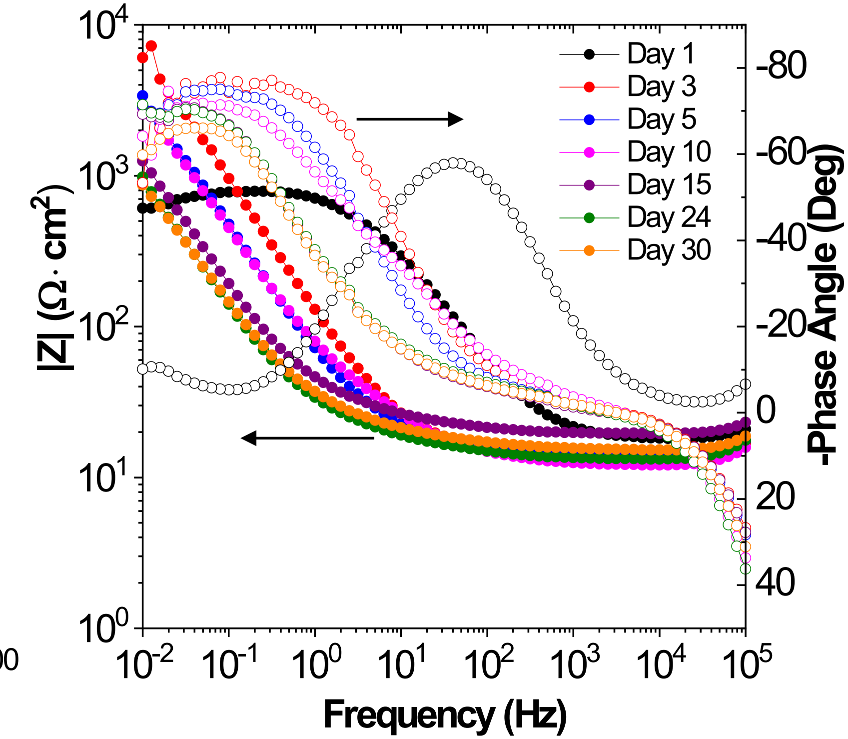
EIS Results for 1094 CGR Sample





The impedance increased for the first three days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

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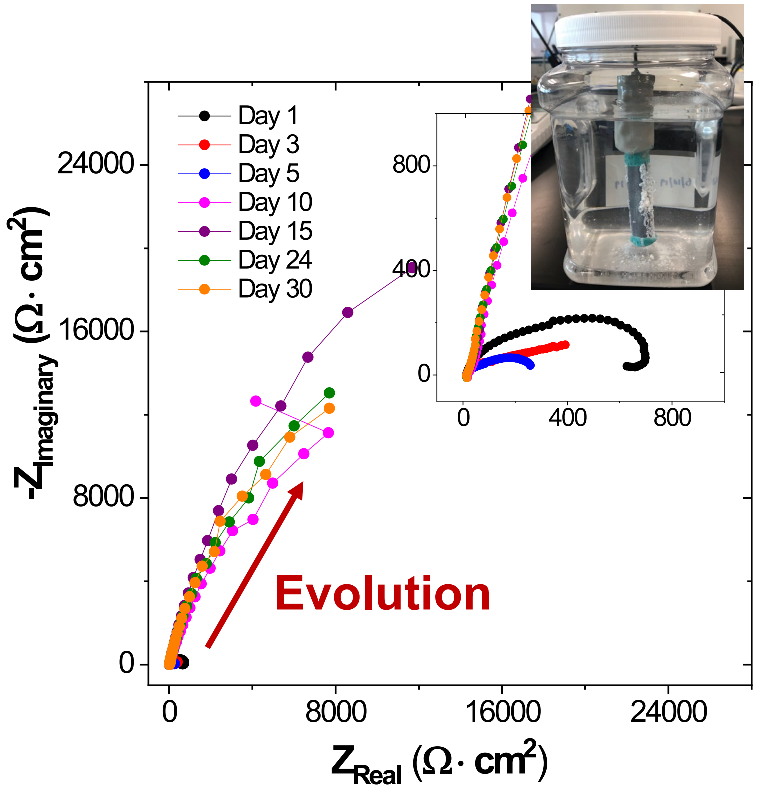
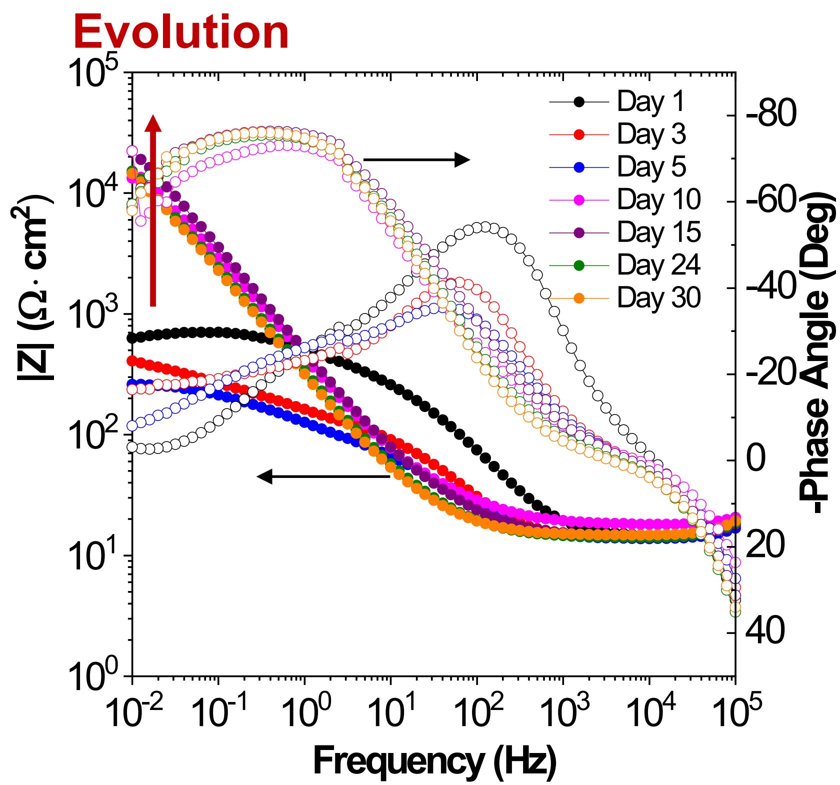
EIS Results for 1094S CGR Sample





The impedance increased for the first five days (formation of zinc corrosion products) and then remained almost constant (corrosion products are stable)

Continuous Immersion Test

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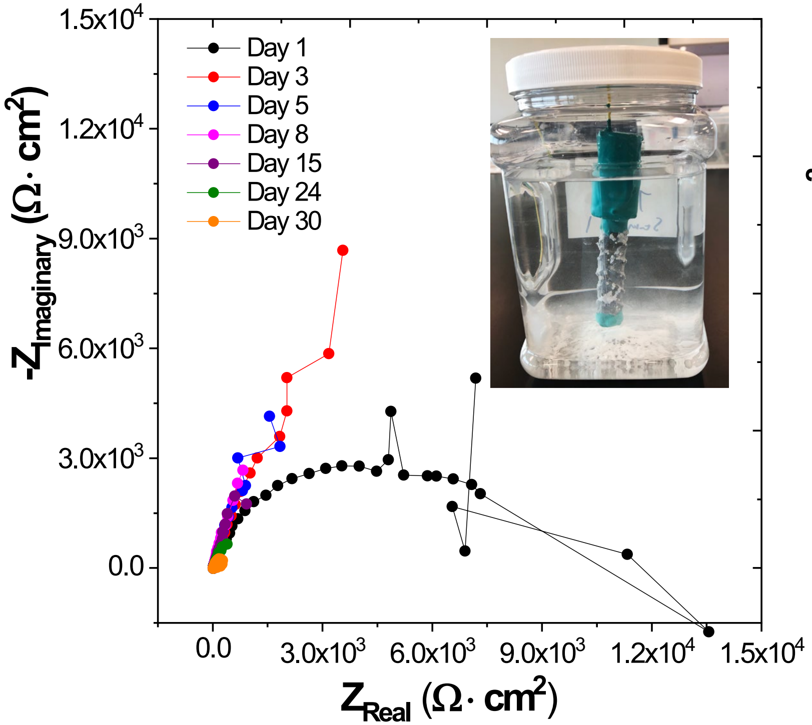
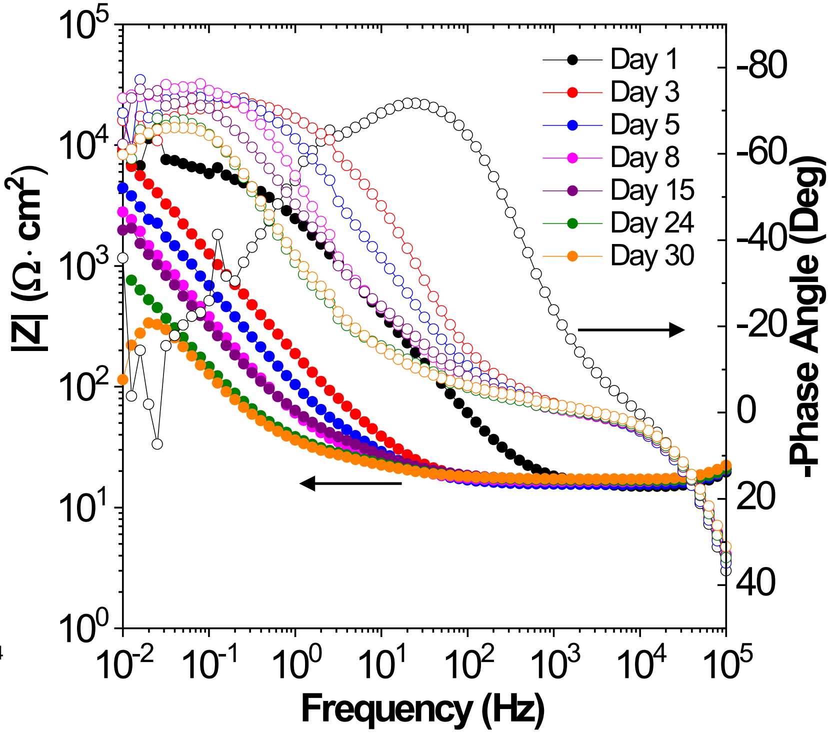
EIS Results for 767 Sample





Impedance decreased gradually with immersion time suggesting zinc dissolution that provided sacrificial protection to the steel rebar

Continuous Immersion Test

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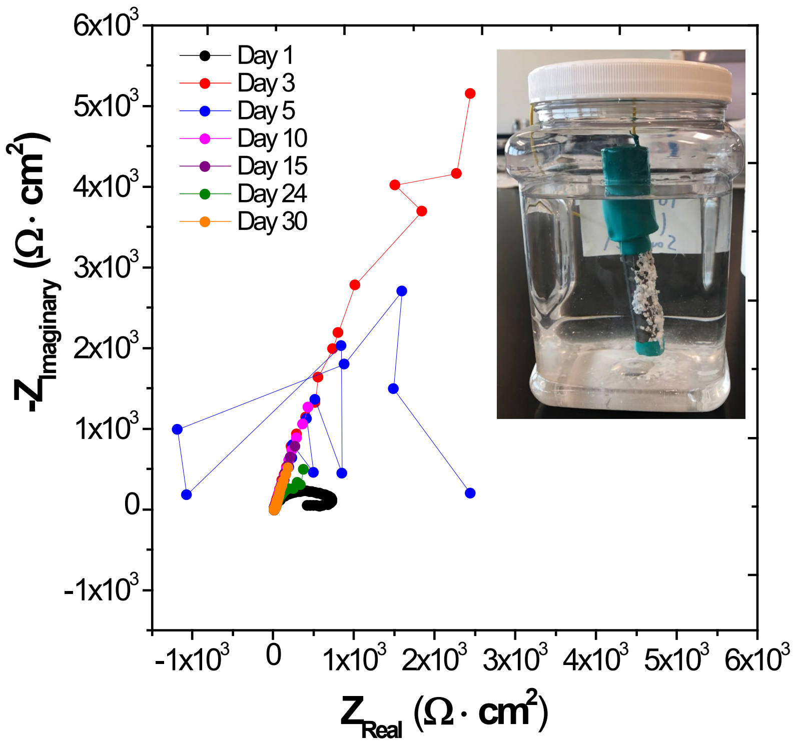
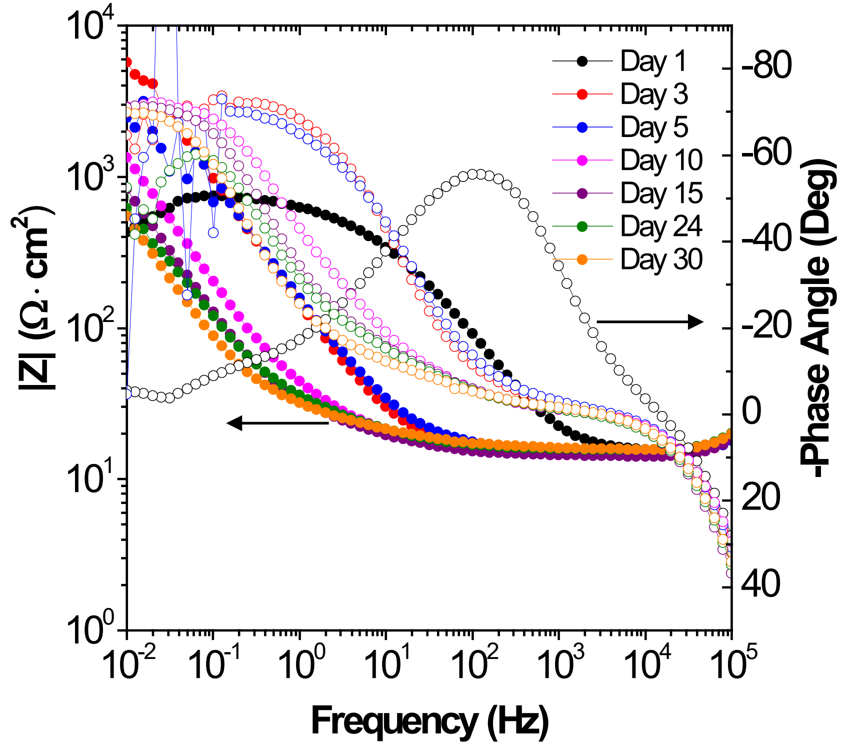
EIS Results for 1035(2) Sample

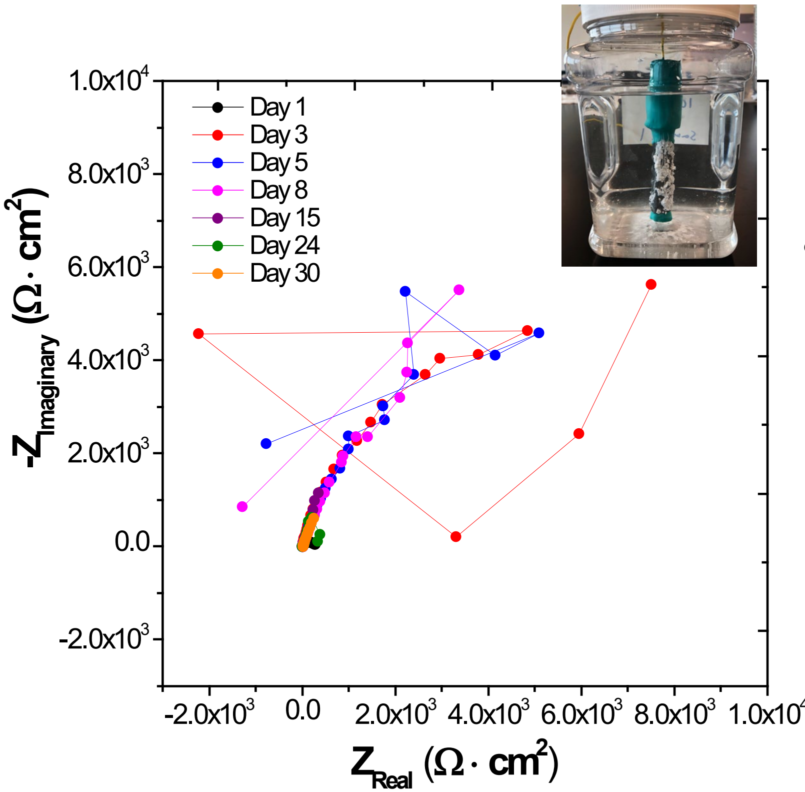


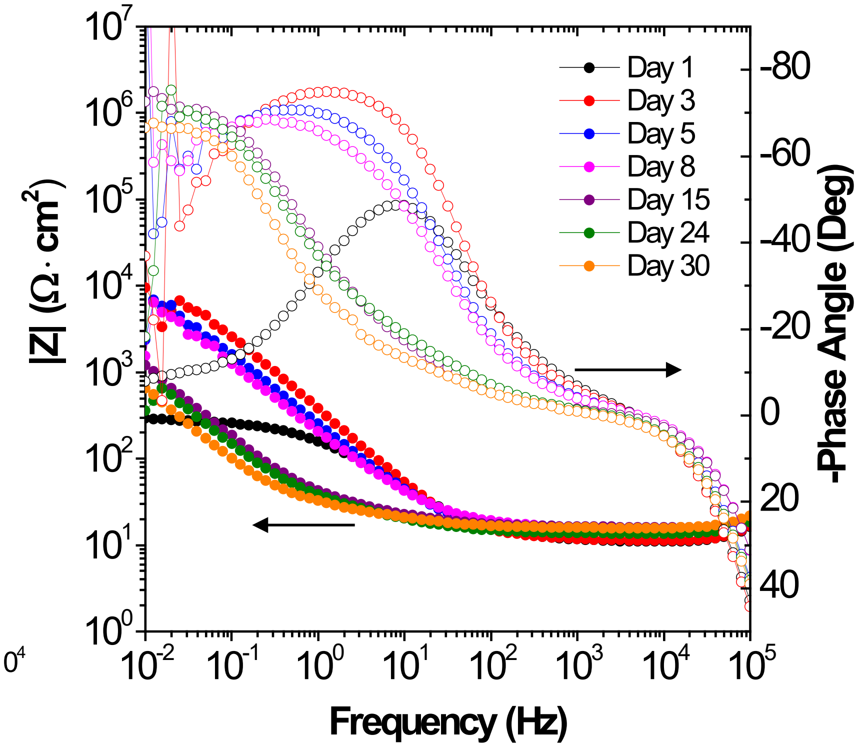


The impedance increased for the first three days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

EIS Results for 1035(4) Sample





The impedance increased for the first eight days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

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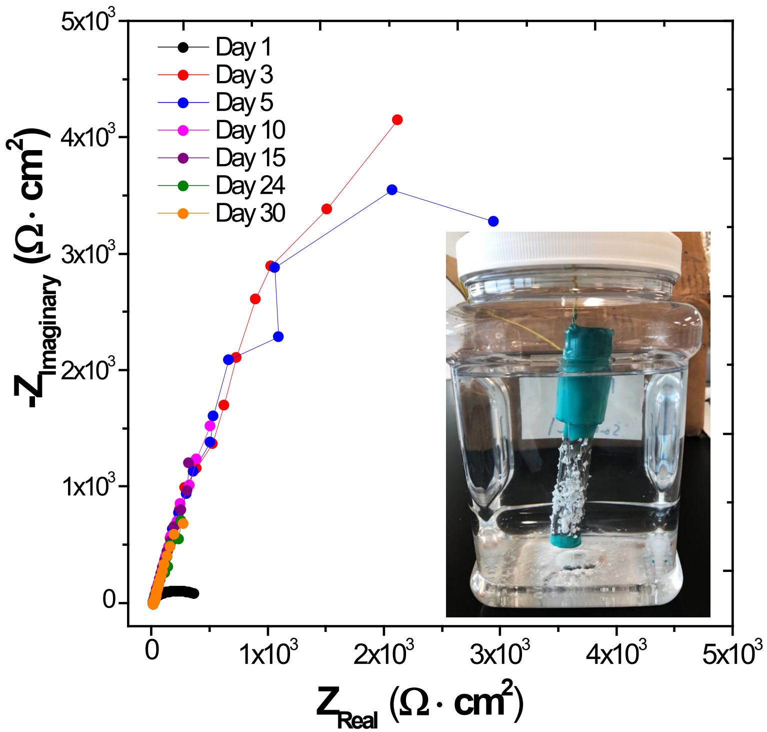
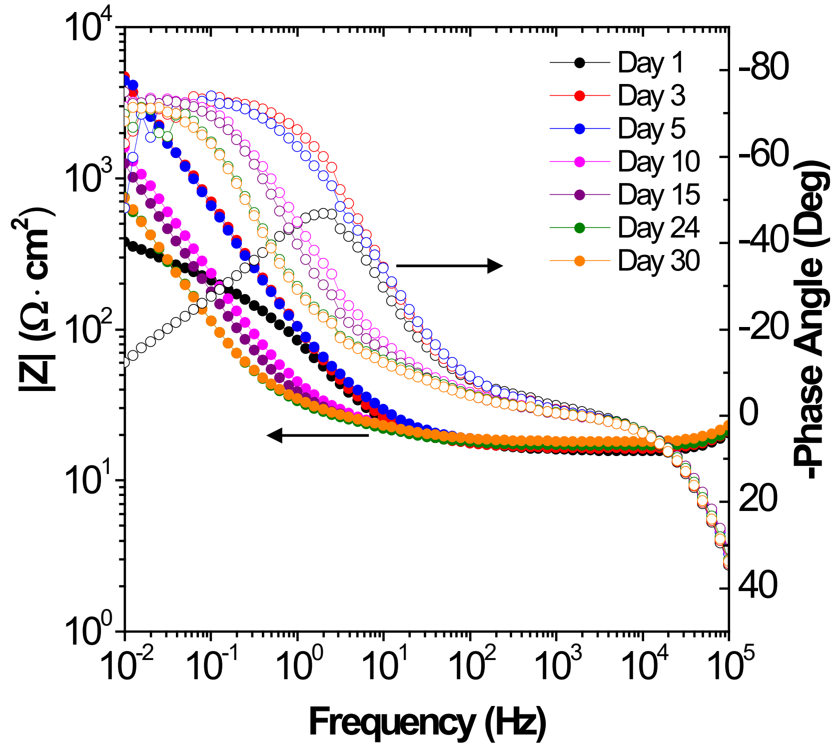
EIS Results for 1035(9) Sample





The impedance increased for the first five days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

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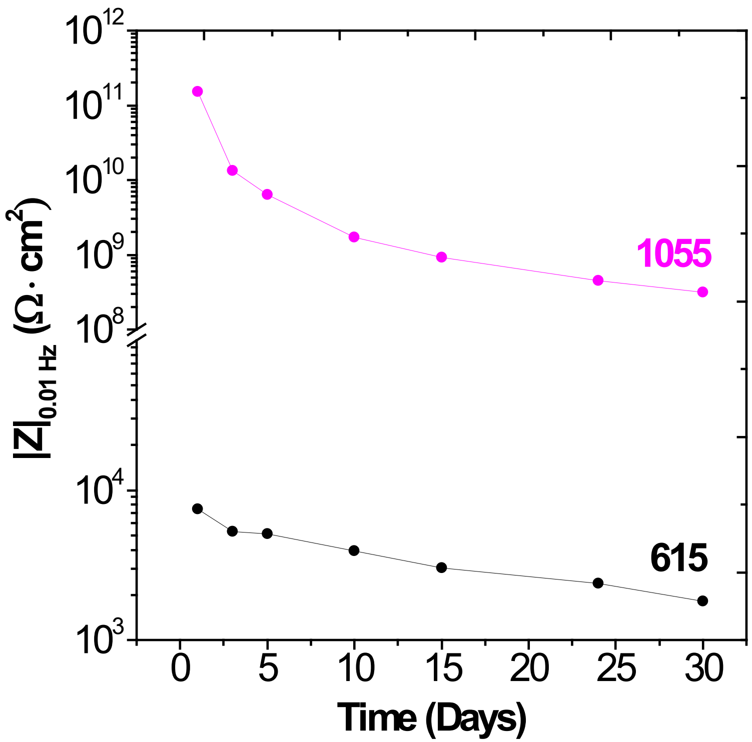
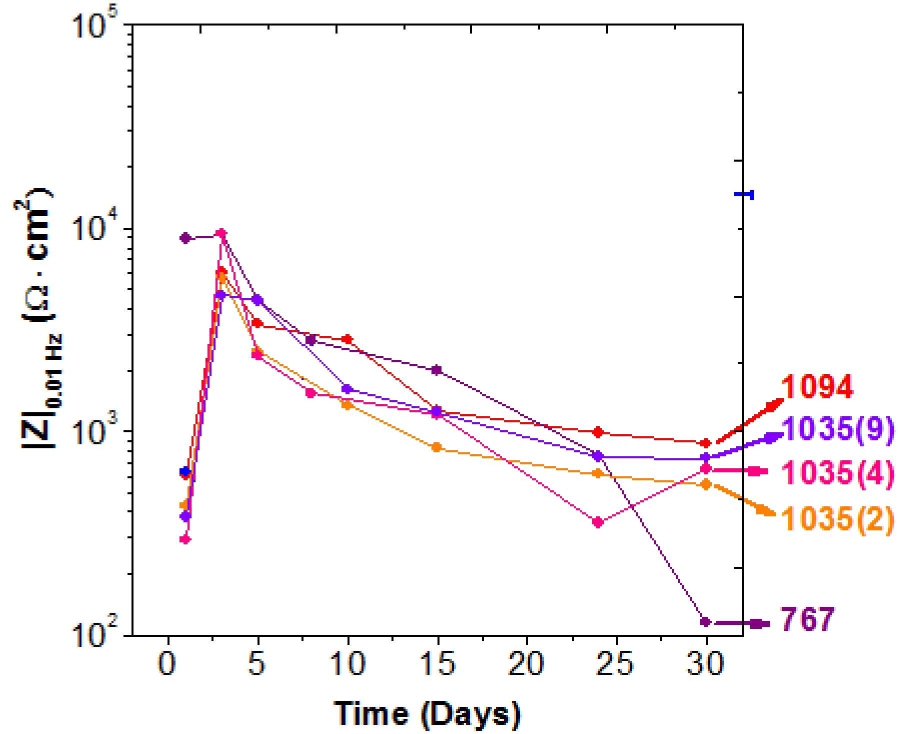
TOTAL IMPEDANCE





Cyclic Fog Chamber Test

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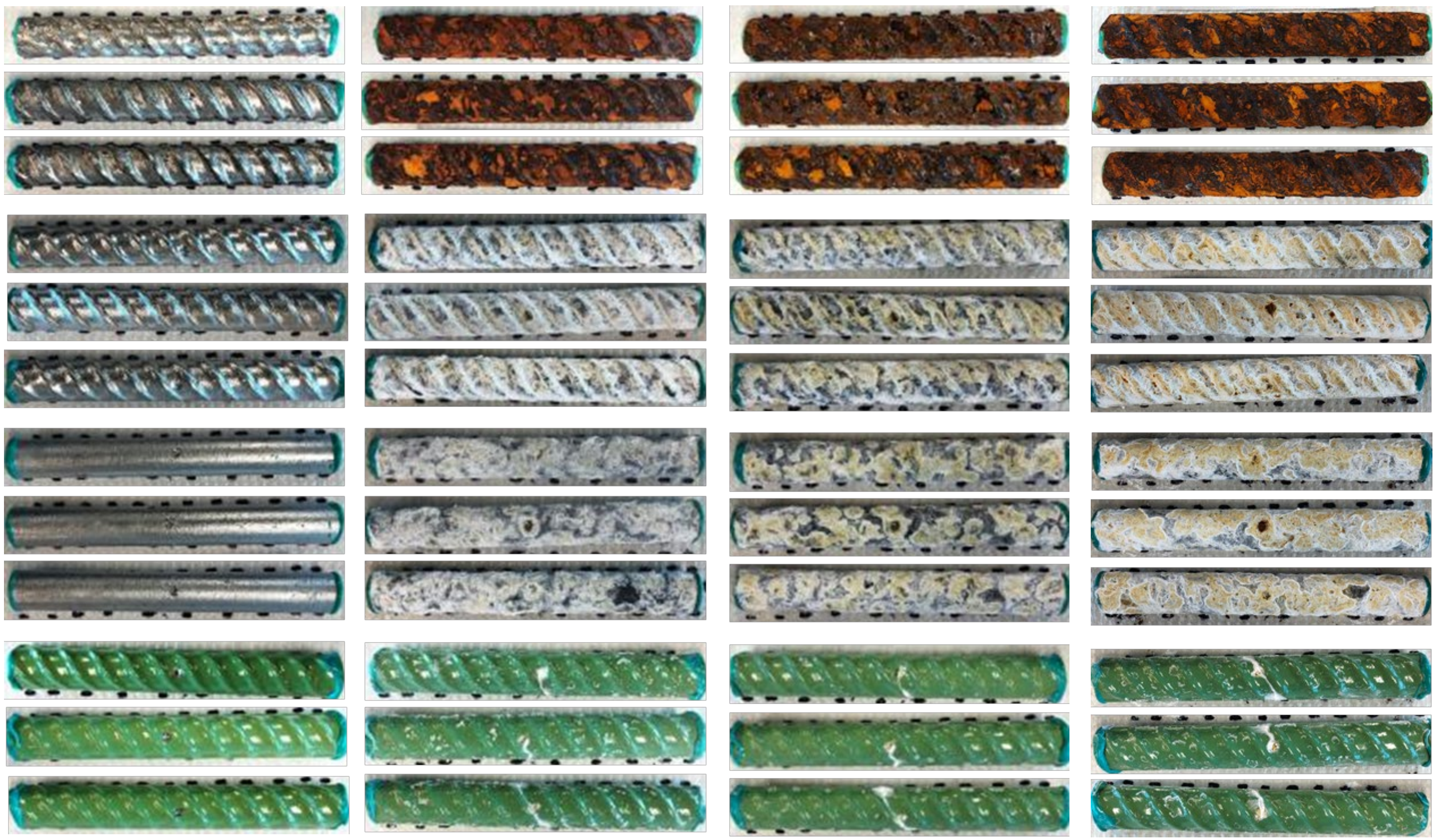
Initial | Cycle 2 | Cycle 5 | Cycle 7



625 (Control)

1094 CGR

1094S

1055 Dual-Coat 1

Cyclic Fog Chamber Test

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Initial | Cycle 2 | Cycle 5 | Cycle 7

Uniform corrosion

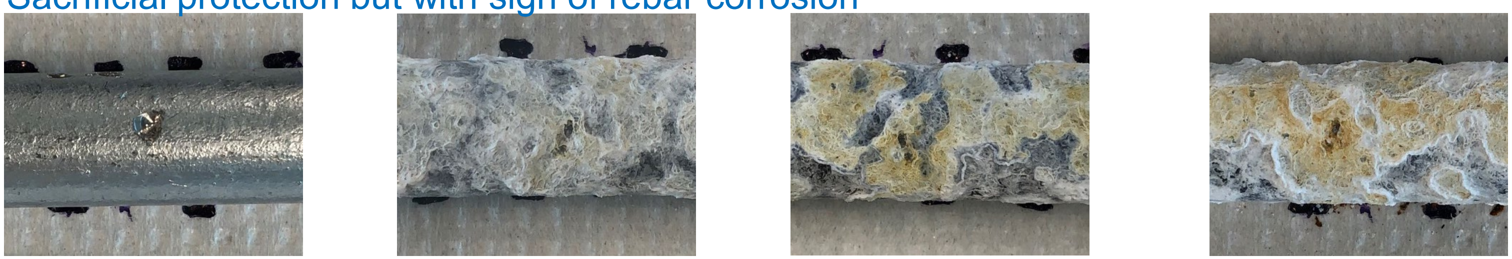
625 (Control)

Sacrificial protection but with sign of rebar corrosion

1094 CGR

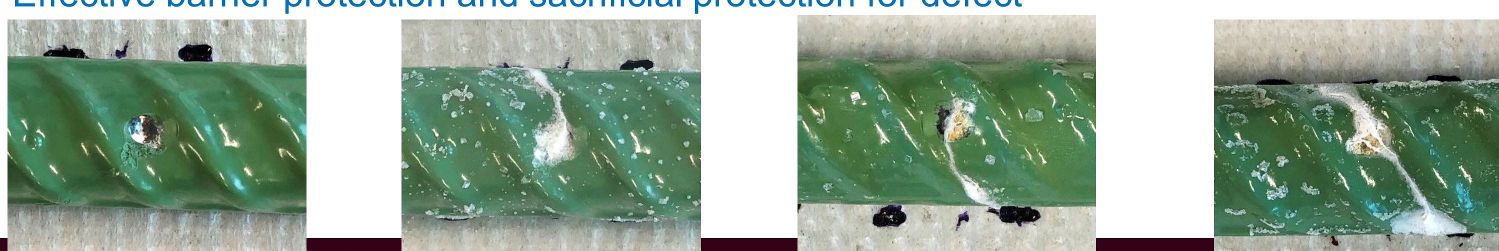
Sacrificial protection but with sign of rebar corrosion

1094S

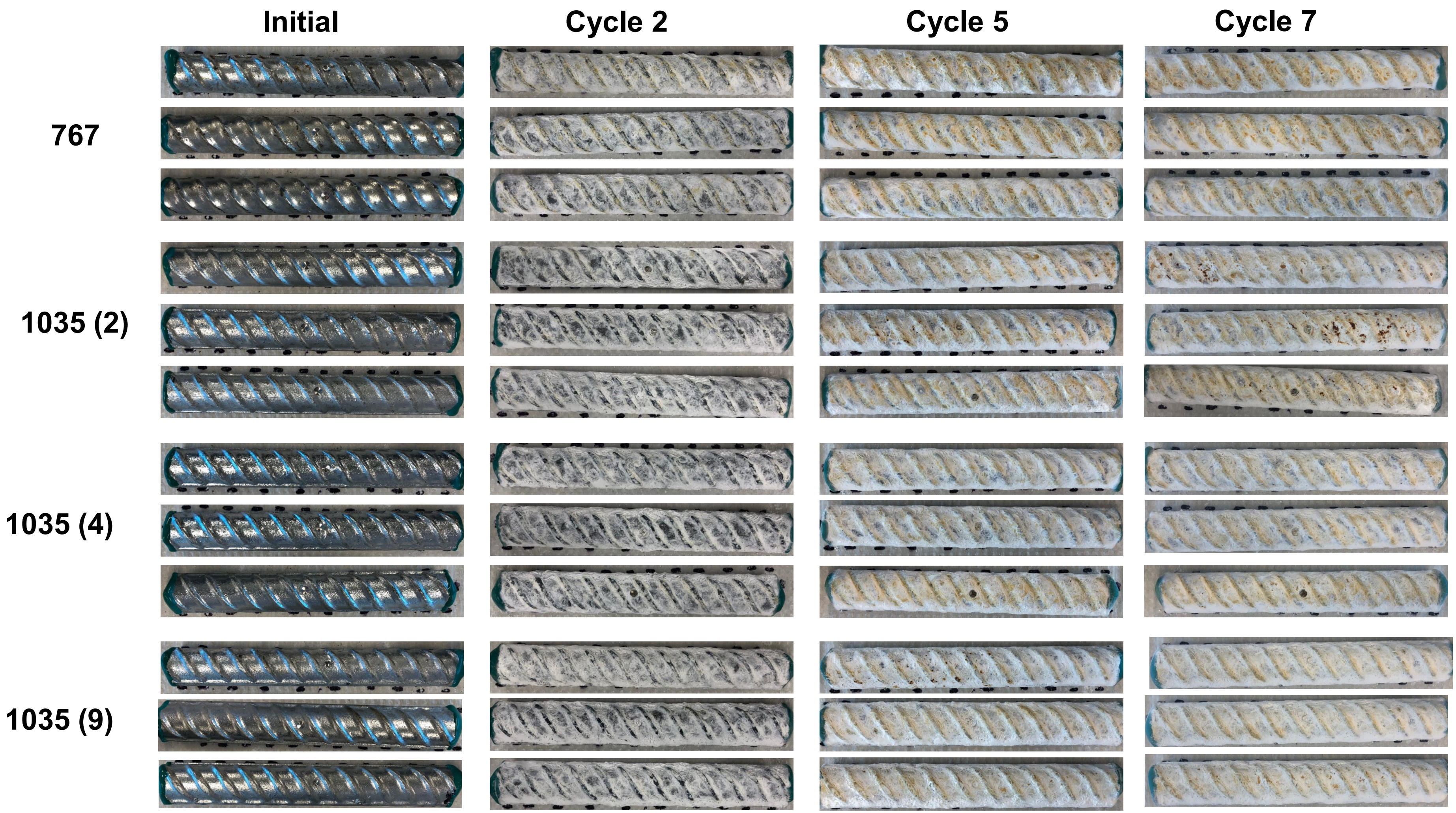


Effective barrier protection and sacrificial protection for defect

1055 Dual-Coat 1



Cyclic Fog Chamber Test



Cyclic Fog Chamber Test

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	Initial	Cycle 2	Cycle 5	Cycle 7

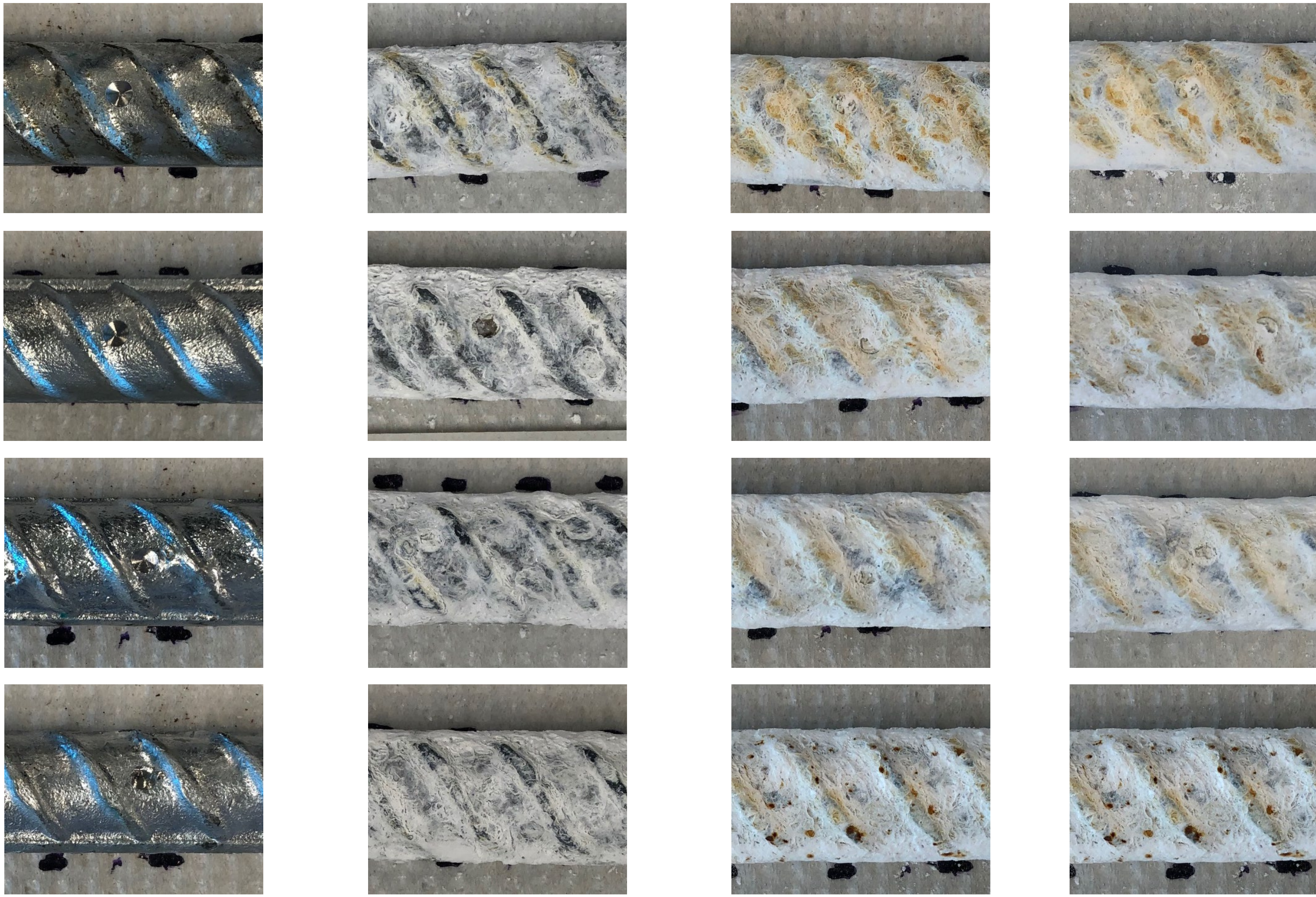
Sacrificial protection at early exposure but with sign of rebar corrosion

767

1035 (2)

1035 (4)

1035 (9)



Cyclic Fog Chamber Test

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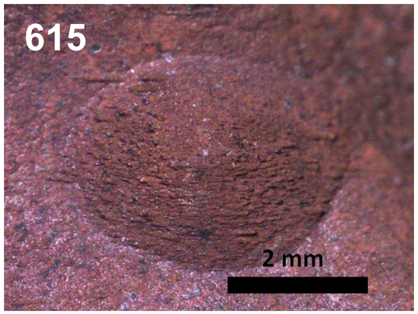
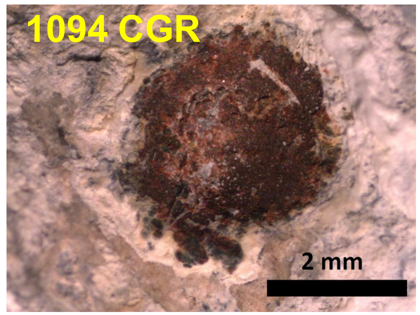
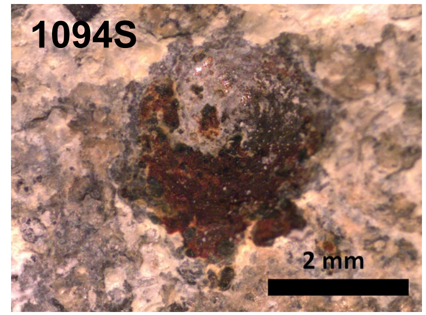
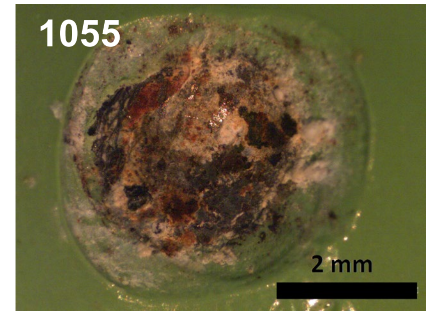
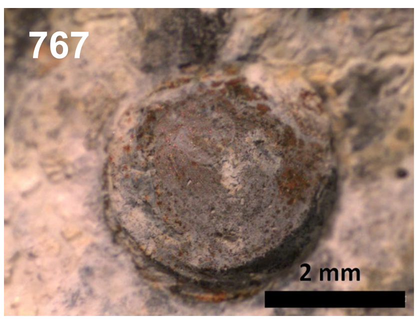
Stereo Microscope Images

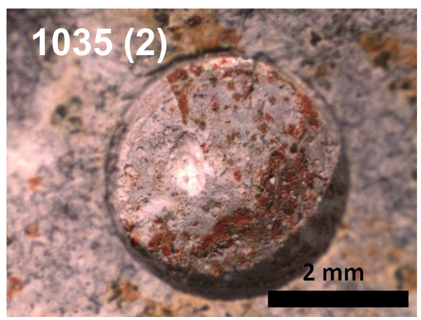


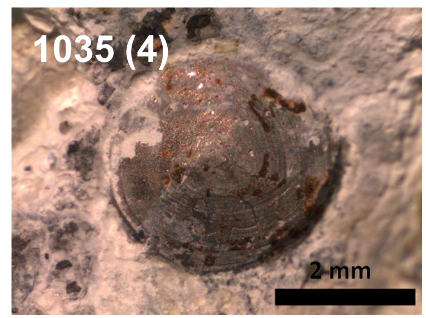


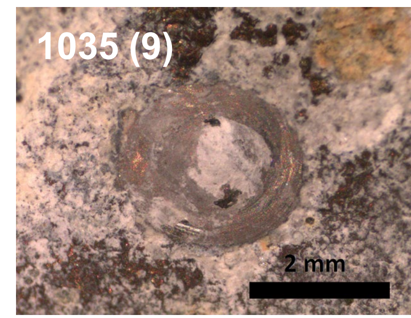


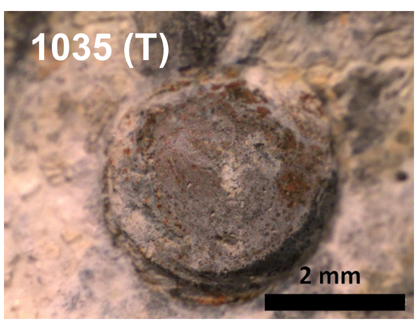






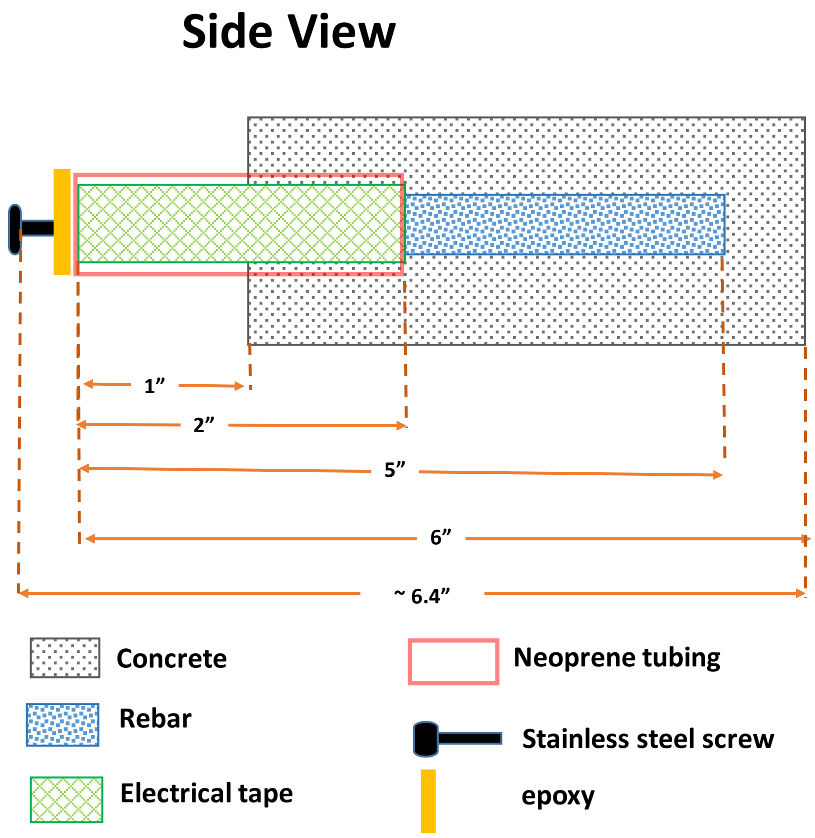


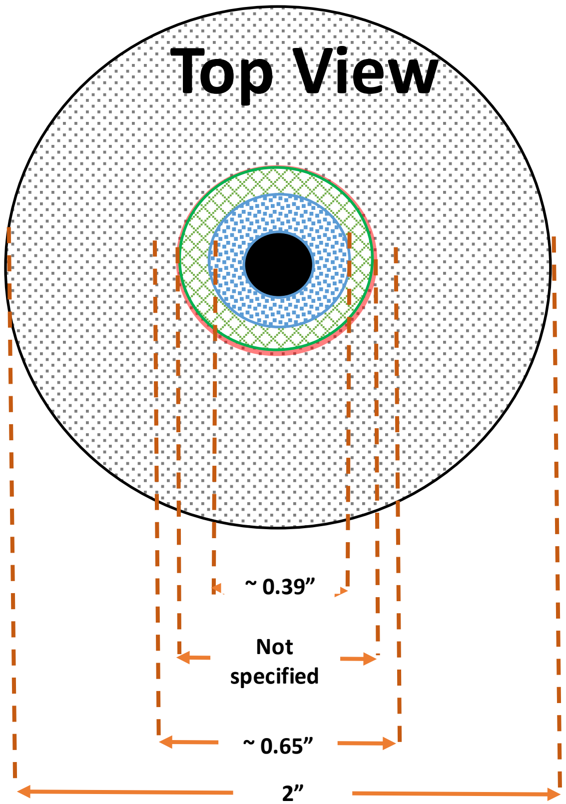




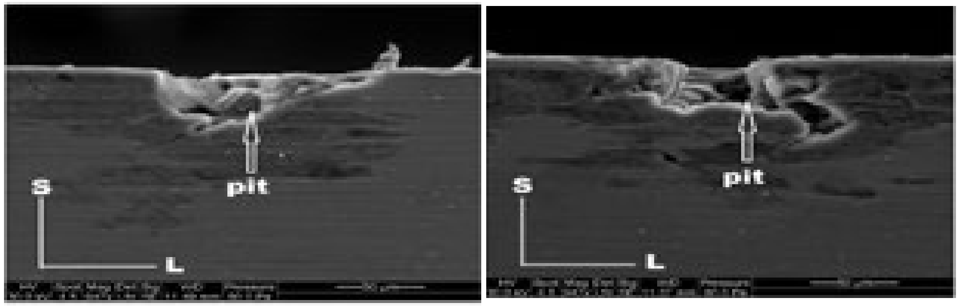
Future Work

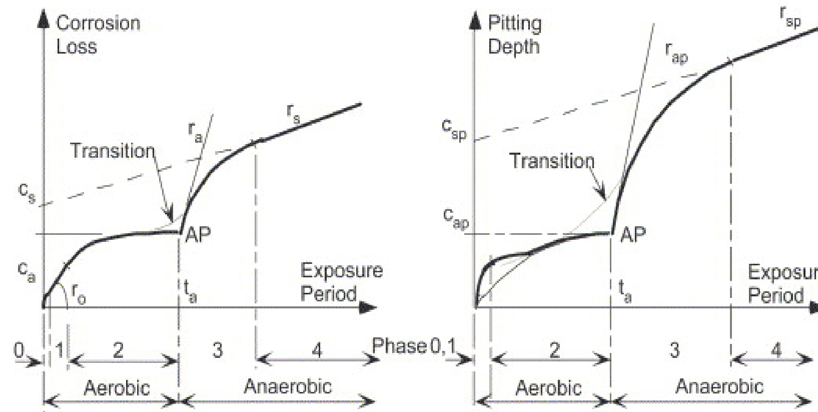
Accelerated and Immersion Test using reinforced concrete samples

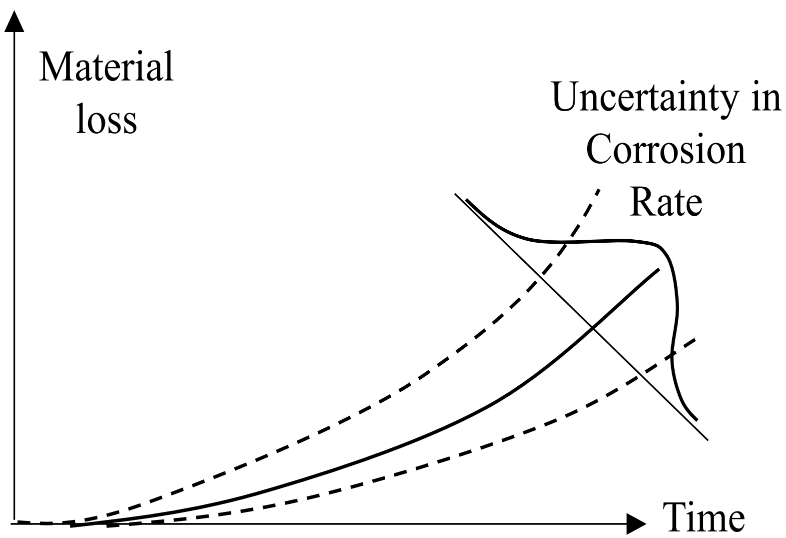


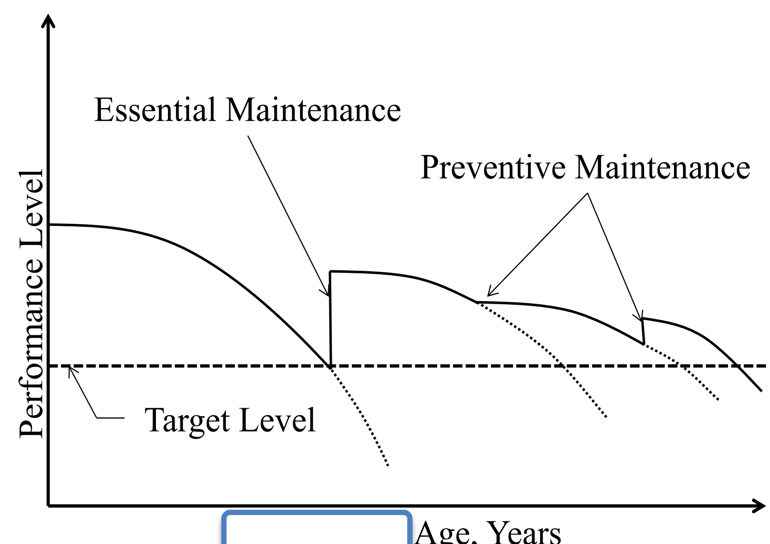


Reliability Modeling









Lifetime target

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- Corrosion protection and performance
  – 45 + years

  Demonstrated

  – 60 + years

  Additional Expected

  – ***105 + years***

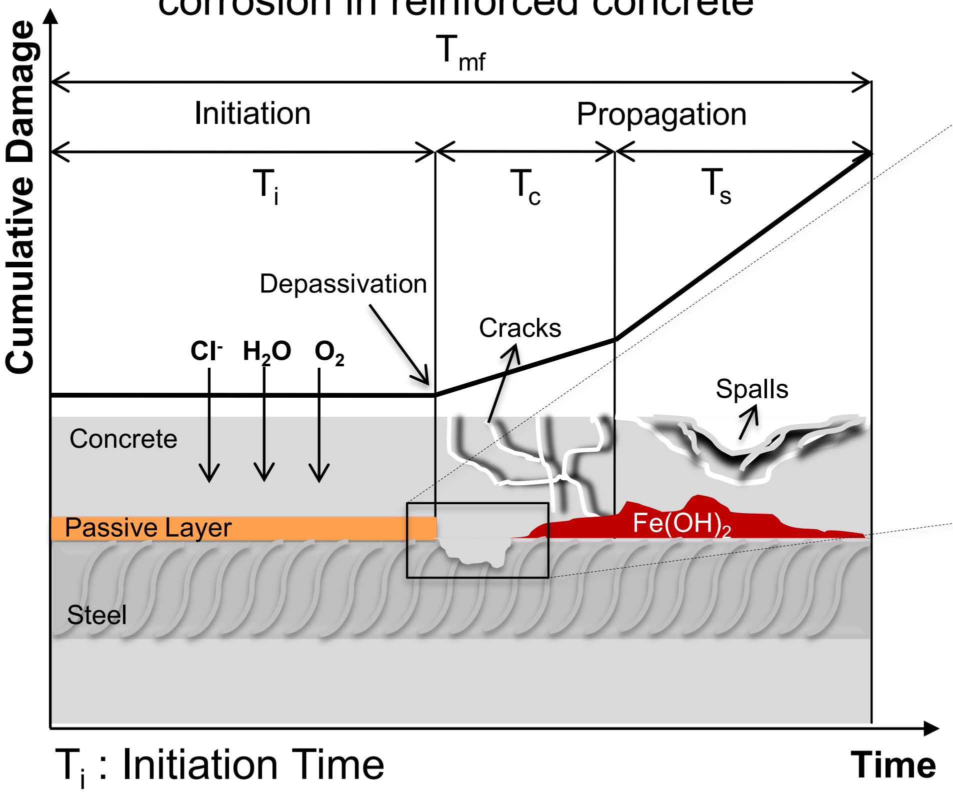
  Remaining

  Service life

Background

Corrosion Mechanism in Reinforced Concrete

Initiation and propagation periods for corrosion in reinforced concrete



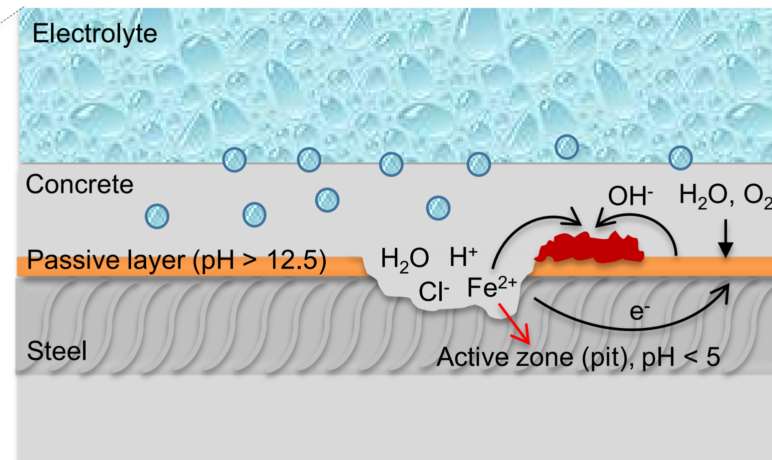
T_i : Initiation Time

T_c : Time for appearance of cracking

T_s : Time for development of spalls

T_{mf} : Maintenance-Free Service Life

Localized attack (pitting corrosion) of reinforcing steel in concrete



Anode (active zone)

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$Fe^{2+} + 2Cl^- \rightarrow FeCl_2$$

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2H^+ + 2Cl^-$$

Cathode (passive layer)

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$$

Hypothesis

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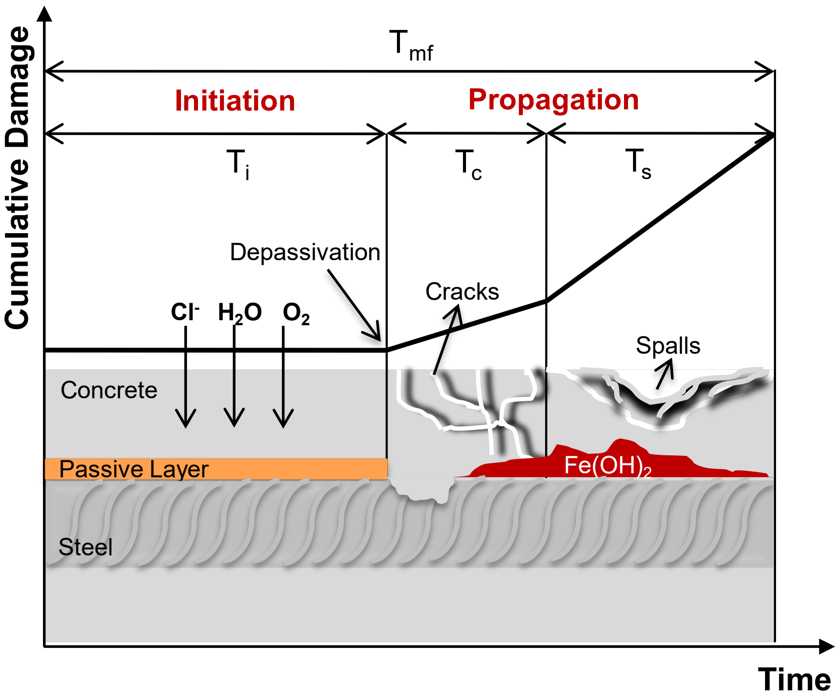
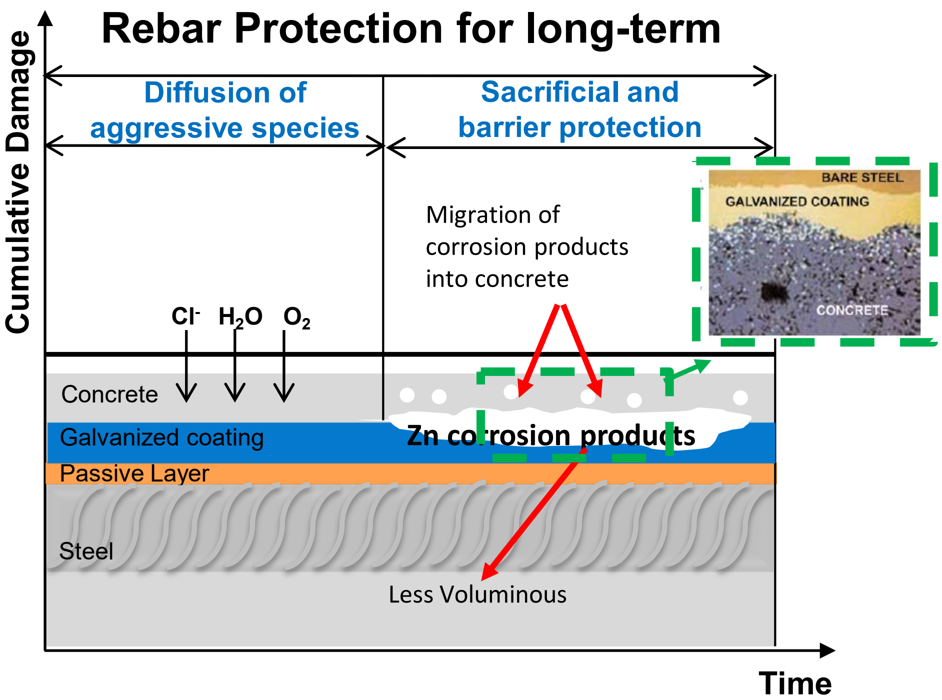
Corrosion Protection using Galvanized Coatings





Background

Coatings for Corrosion Protection

Protective coatings have been recognized as one of the most effective methods to protect reinforced concrete from corrosion

Coatings provide protection by:

- **Barrier Protection**
  - Fusion Bonded Epoxy
- **Cathodic and Barrier Protection**
  - Galvanized Steel

Objectives

Current Progress

- Conducting laboratory steady state aging conditions on different rebar materials used for reinforced concrete.
- Conducting laboratory accelerating testing conditions on different rebar materials used for reinforced concrete.
- Conducting laboratory testing conditions on RC samples.
- Conducting simulation of cycling harsh environment existed in the salt belt conditions (as unique and practical case in the USA).
- Conducting theoretical modeling based on dissolution mechanism and failures due to corrosion process and set up the basis for reliability modeling.

Materials

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PHASE I

- 615 Control (Bare Carbon Steel)
- 1094 CGR (Continuous Galvanized Reinforced Rebar)
- 1094S CGR Smooth
- 1055 Dual-Coat (CGR + Epoxy)
- 767 Galvanized Steel
- 1035 Dual-Coat (MMFX steel + CGR)
  - 1035 (2)
  - 1035 (4)
  - 1035 (9)
  - 1035 (T)

MMFX – Martensitic Microcomposite Formable Steel

Corrosive Environments

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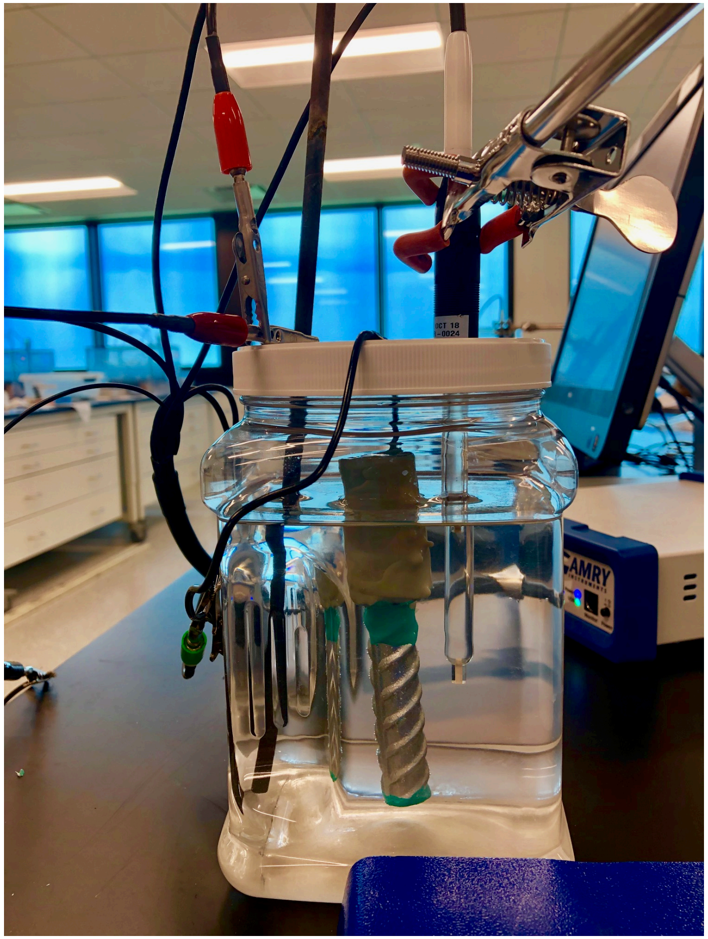
Continuous Salt Immersion Test

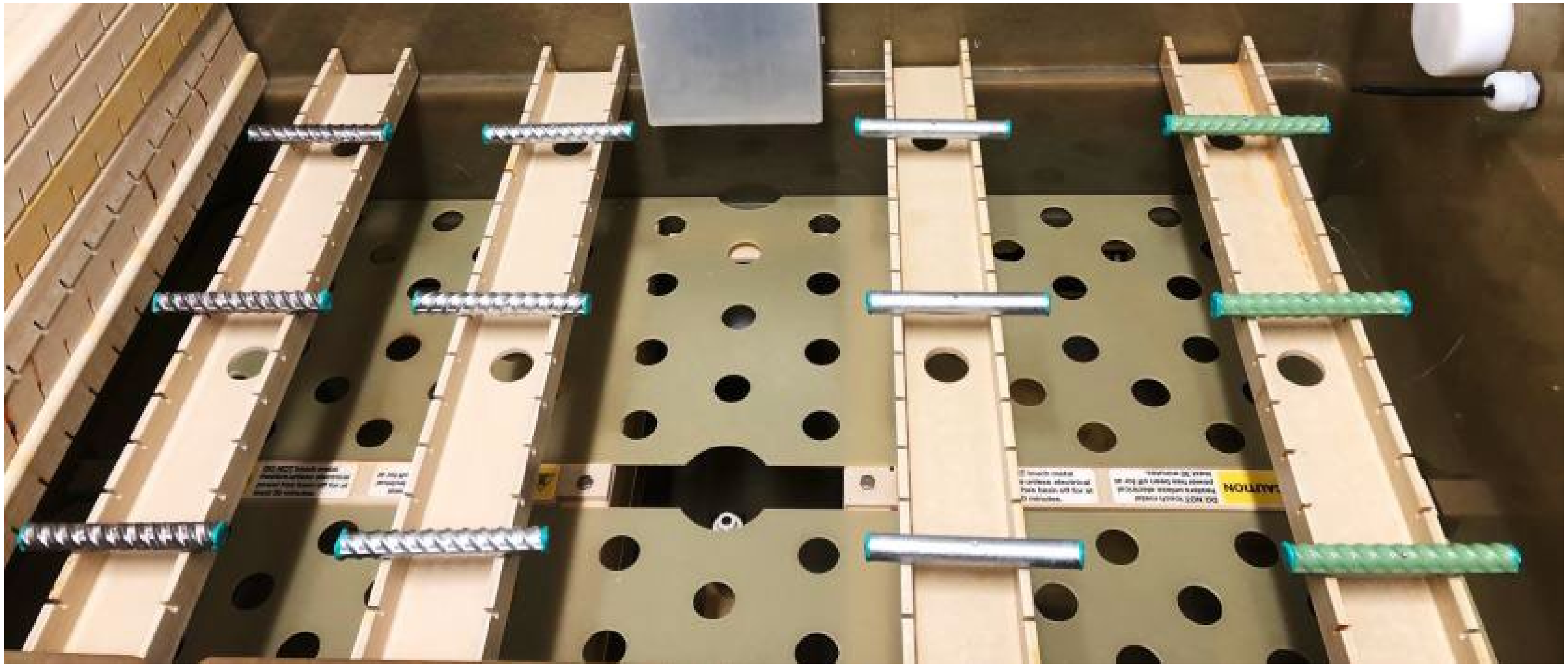


- Electrolyte: Concrete Pore Solution: (0.08 M KOH, 0.02 M NaOH, 0.001 M $Ca(OH)_2$, 0.5 M NaCl)
- pH~12-13
- Immersion Time: 30 days
- Electrochemical Testing:
  - OCP: 10 min
  - EIS (100 kHz-10 mHz)
- Three-electrode Cell Configuration:
  - Reference: Saturated Calomel Electrode (SCE)
  - Counter: Graphite
  - Working: Rebar samples

Corrosive Environments

Cyclic Fog Chamber Test

- Cyclic Duration: 48 h wet / 48h dry for 7 cycles (28 days)
- Electrolyte: 5 wt.% NaCl
- Temperature: 35°C



Corrosive Environments

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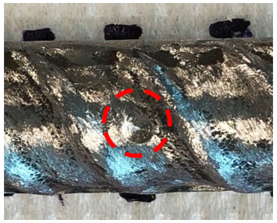
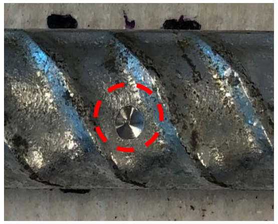
Cyclic Fog Chamber Test

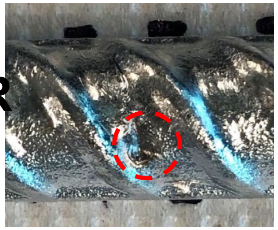
615



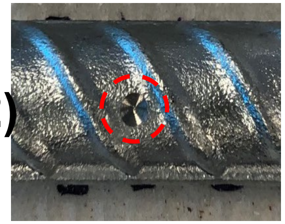
767



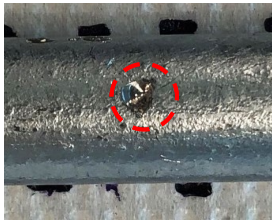
1094 CGR



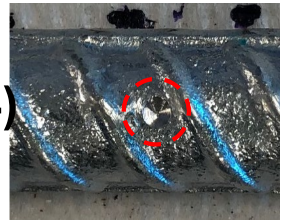
1035 (2)



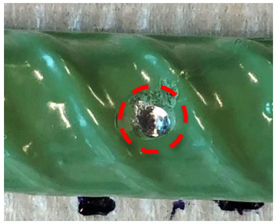
1094S



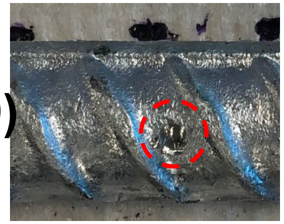
1035 (4)



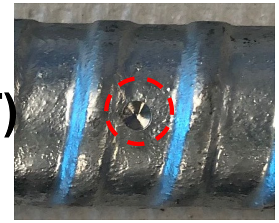
105
5



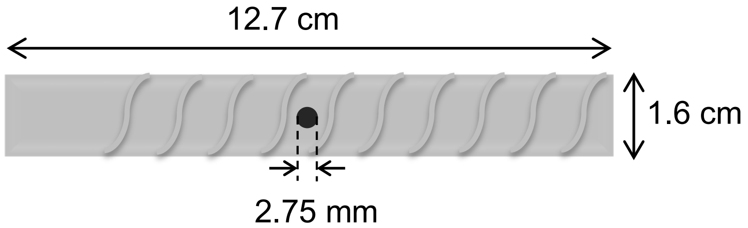
1035 (9)



1035 (T)



Rebar dimensions



Rebar samples were drilled with a 1/8” bit for 1 mm of penetration

Continuous Immersion Test

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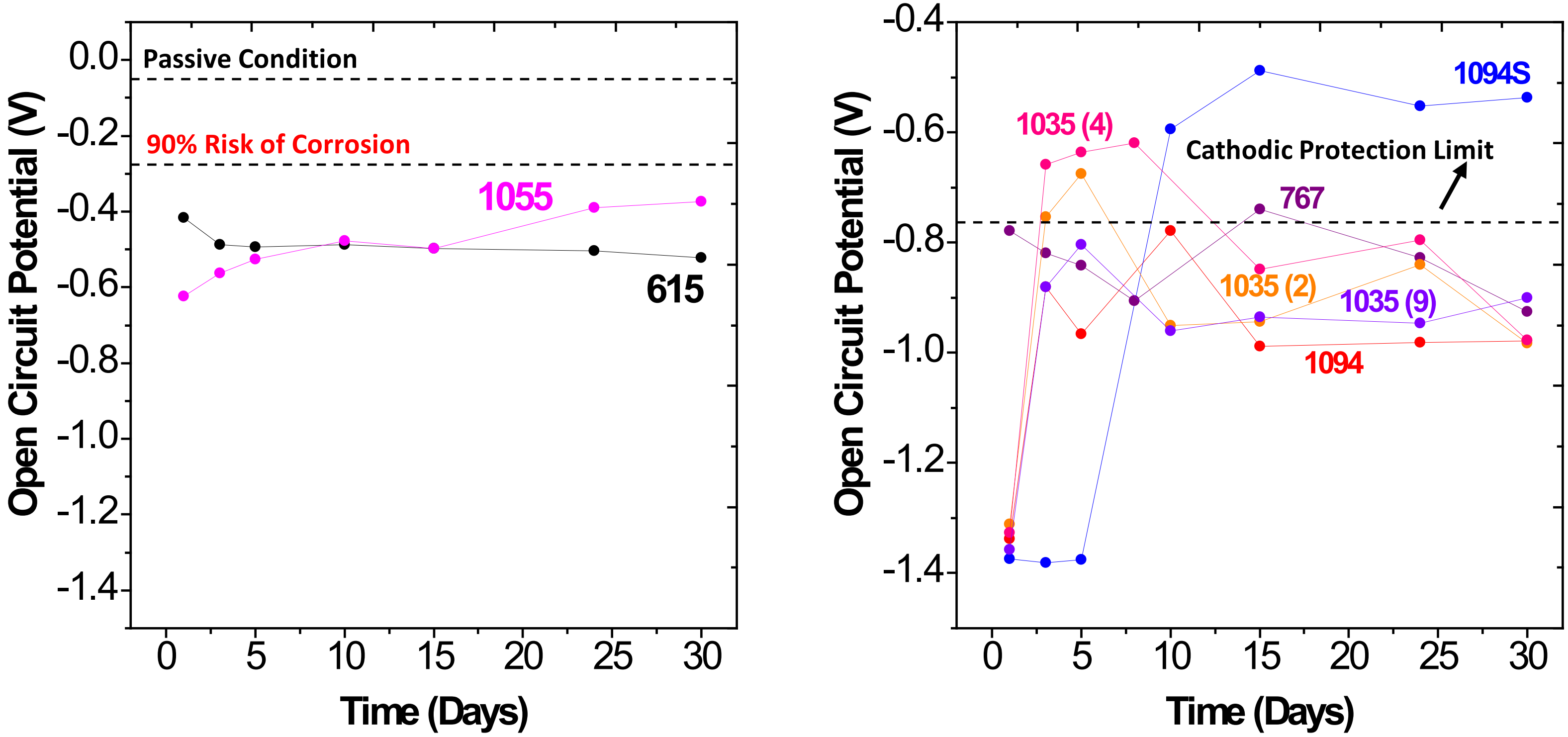
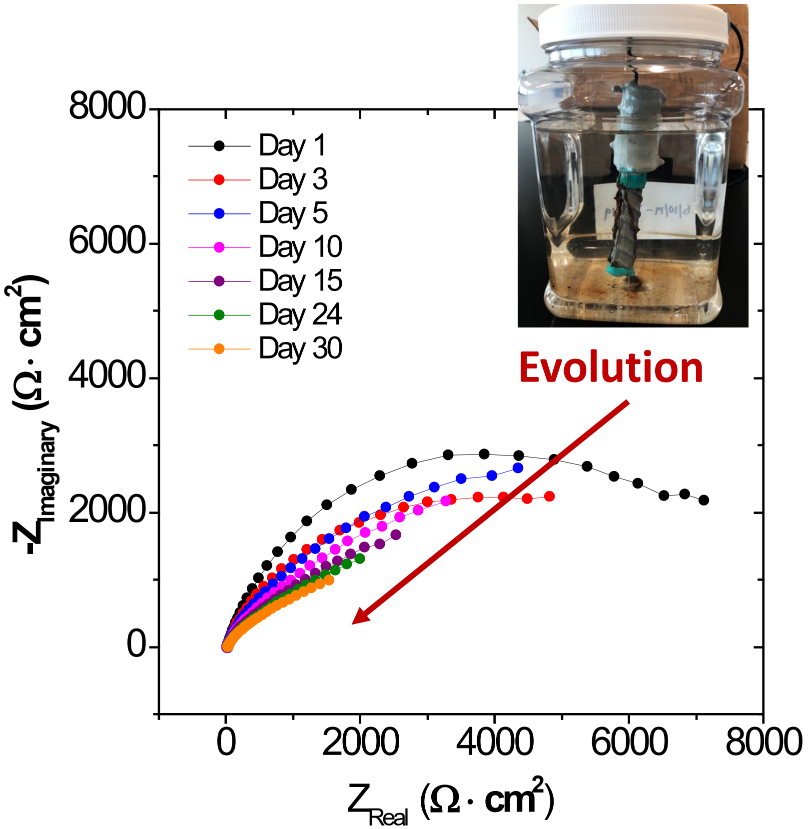
OCP Results

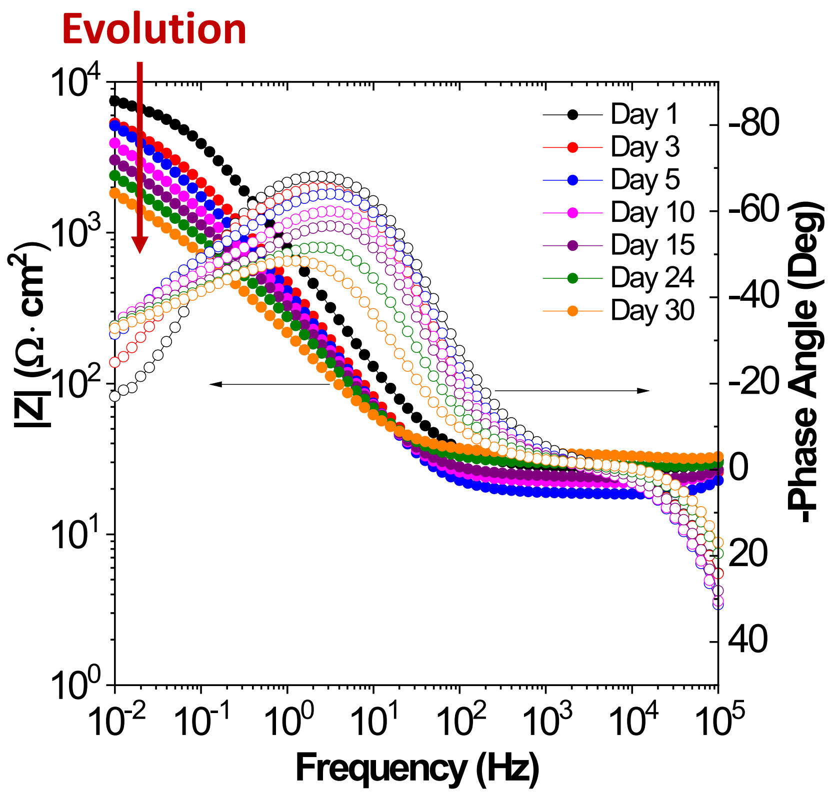


The majority of the different coatings (except the 1055 Epoxy coating) provided sacrificial protection to the carbon steel rebar

Continuous Immersion Test

EIS Results for 615 Control Sample

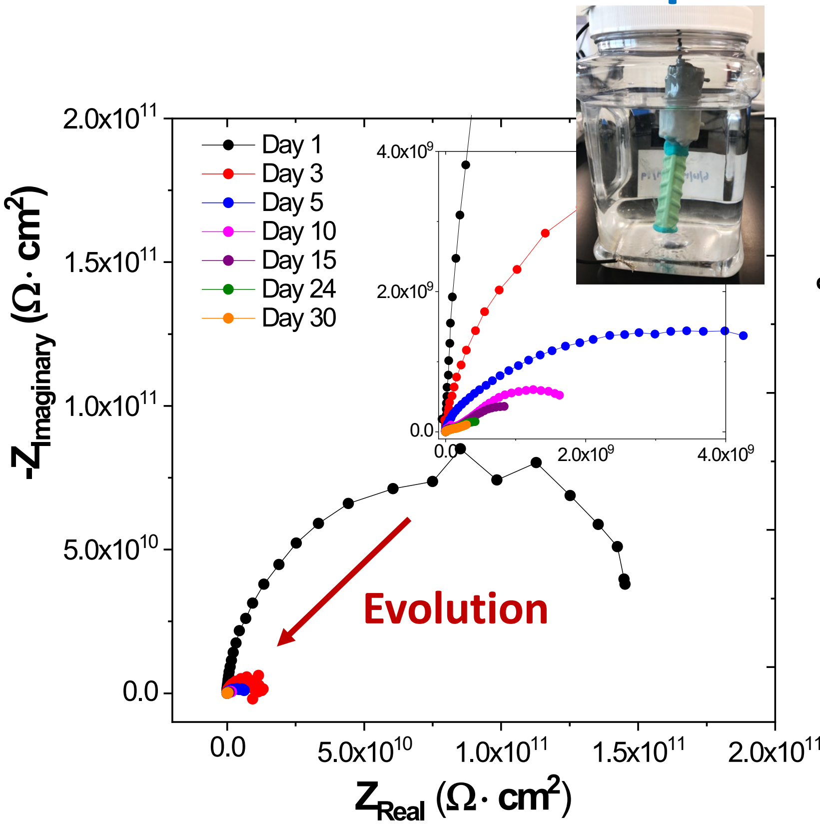


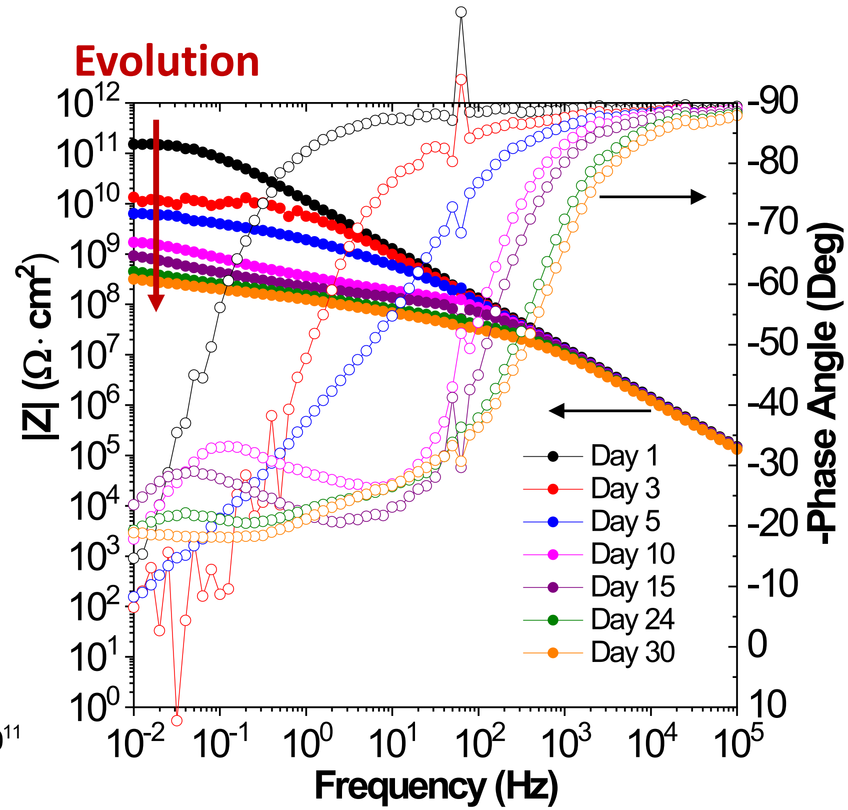


The impedance gradually decrease overtime suggesting a continuous degradation of the carbon steel substrate

Continuous Immersion Test

EIS Results for 1055 Sample





High impedance values due to excellent barrier protection, however impedance decreased overtime as a result of water penetration and initiation of corrosion processes at the carbon steel substrate (presence of a second time constant after 10 days of immersion)

Continuous Immersion Test

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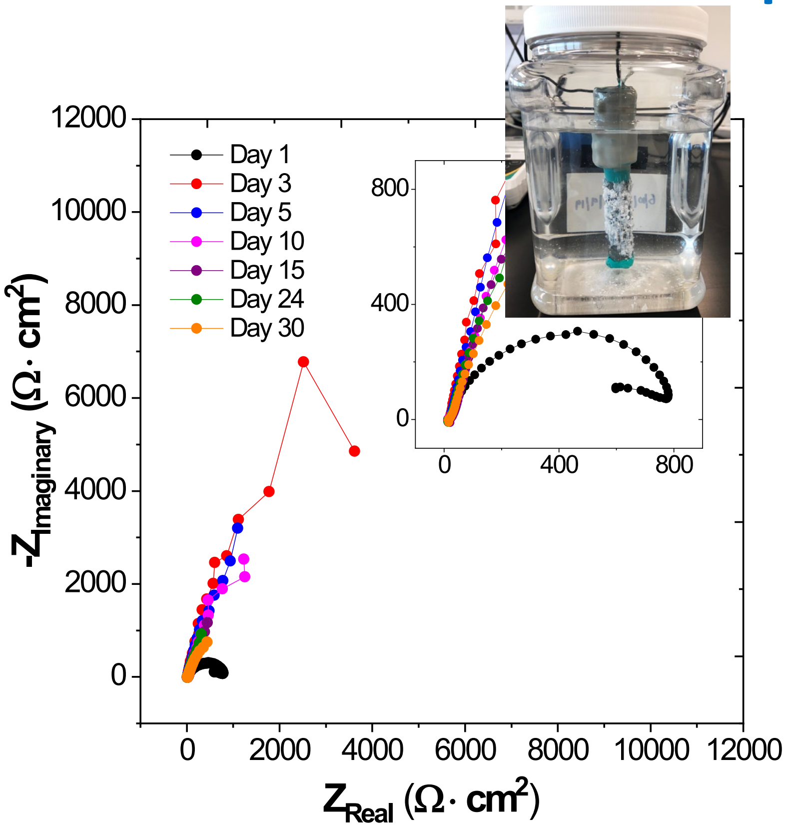
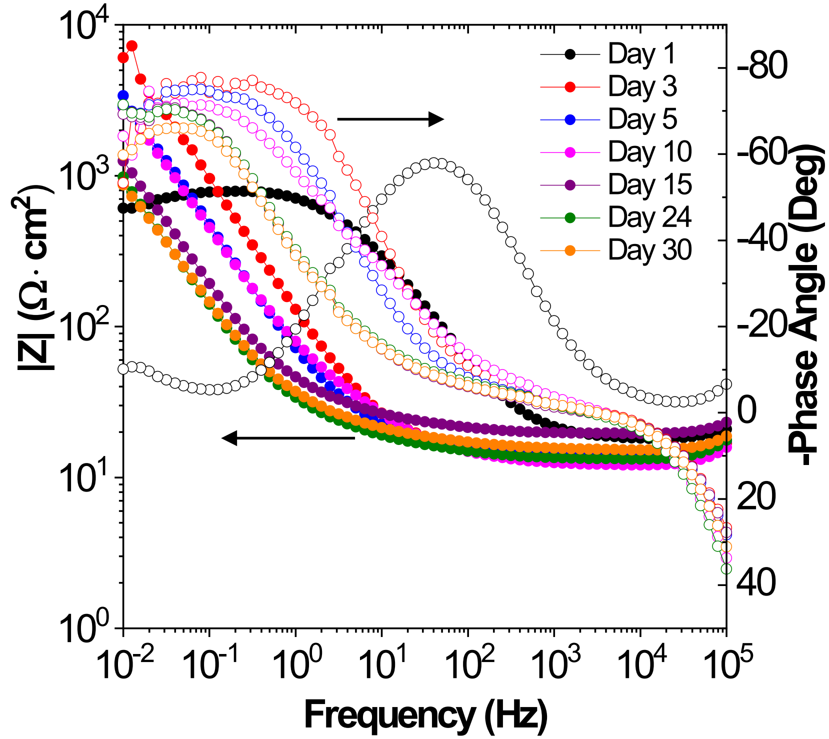
EIS Results for 1094 CGR Sample





The impedance increased for the first three days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

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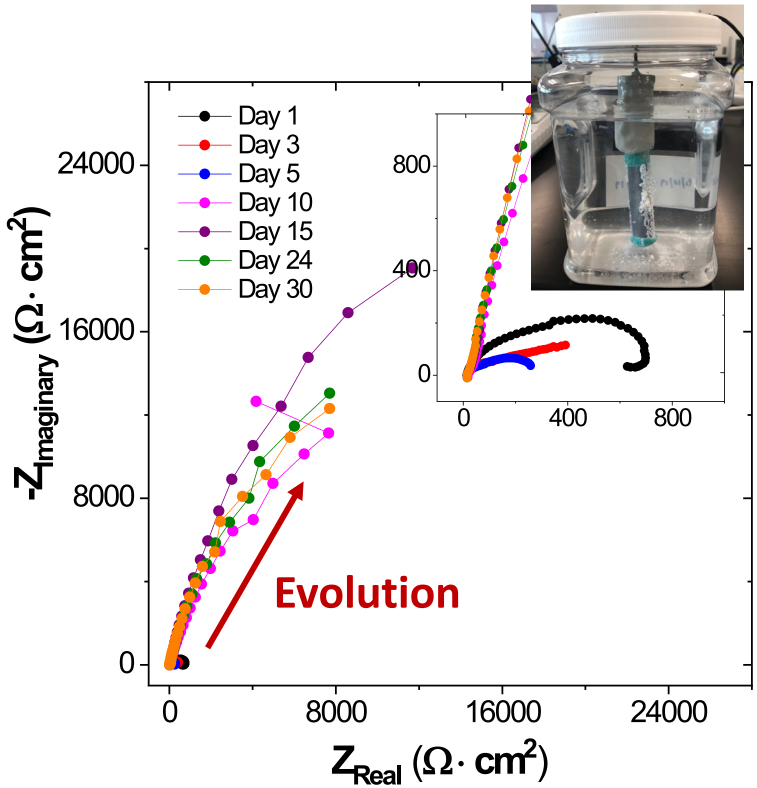
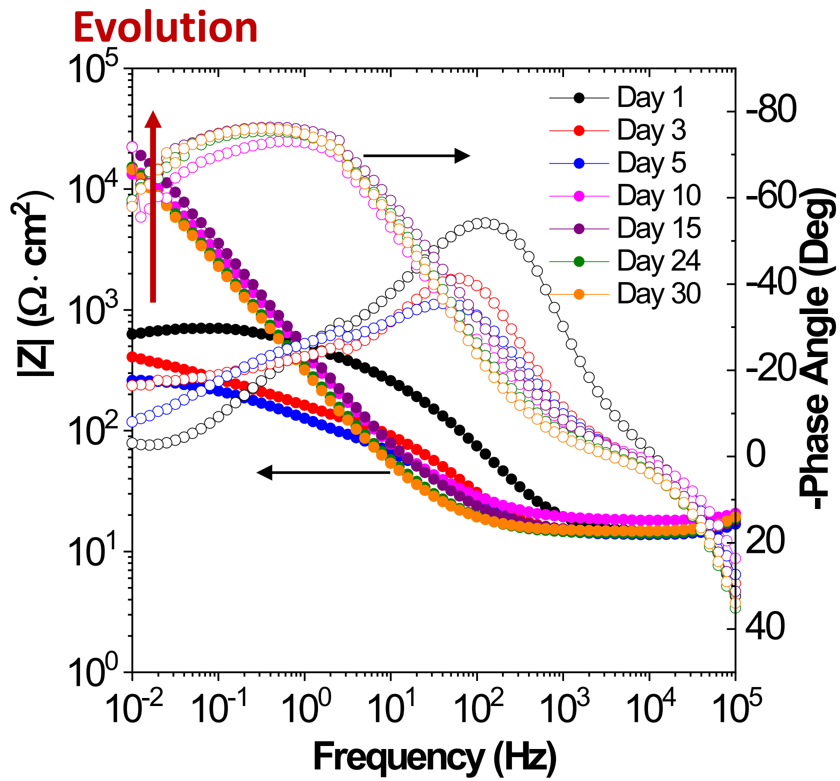
EIS Results for 1094S CGR Sample

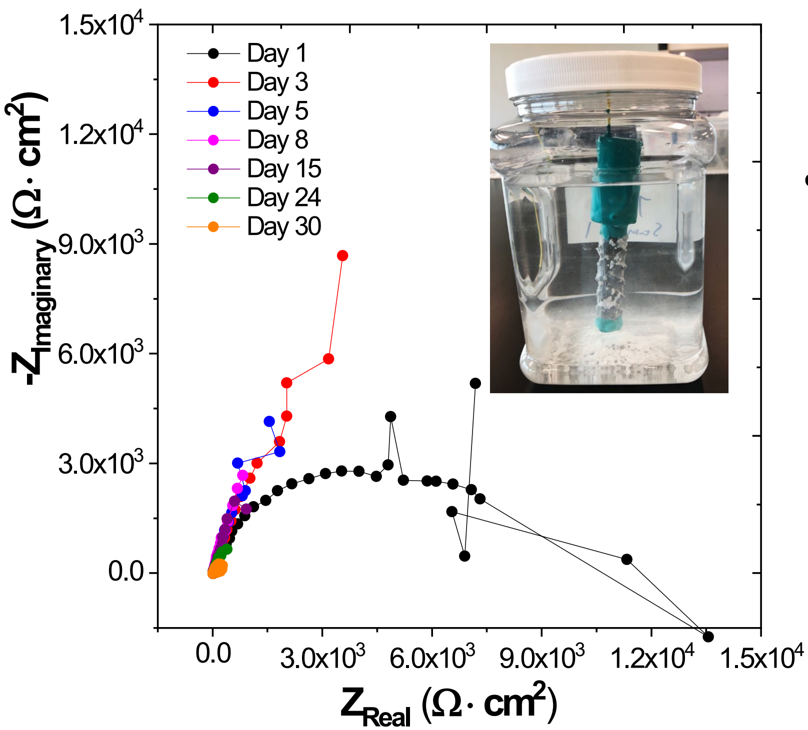


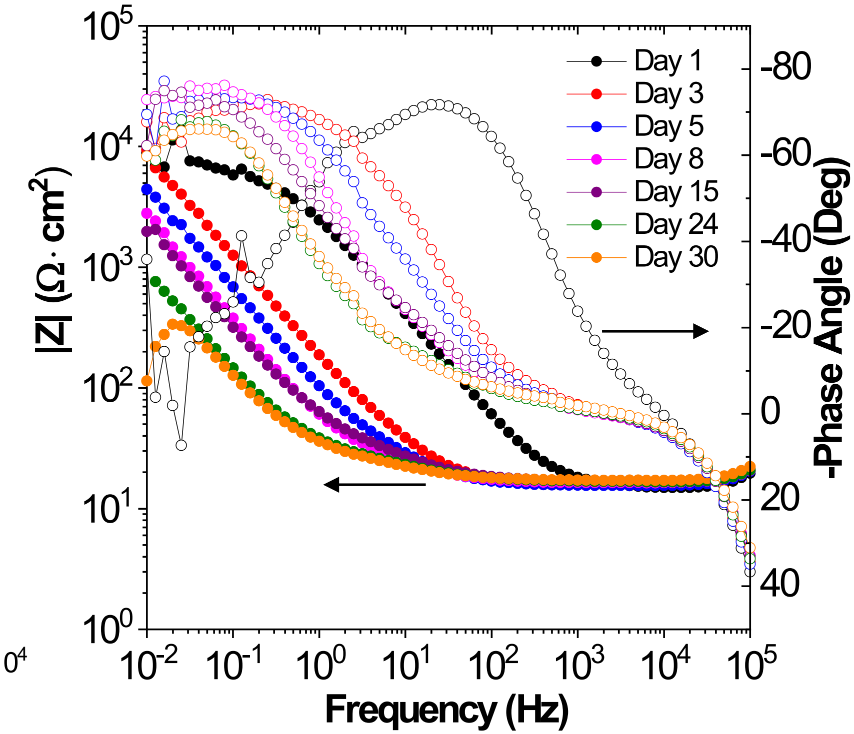


The impedance increased for the first five days (formation of zinc corrosion products) and then remained almost constant (corrosion products are stable)

Continuous Immersion Test

EIS Results for 767 Sample

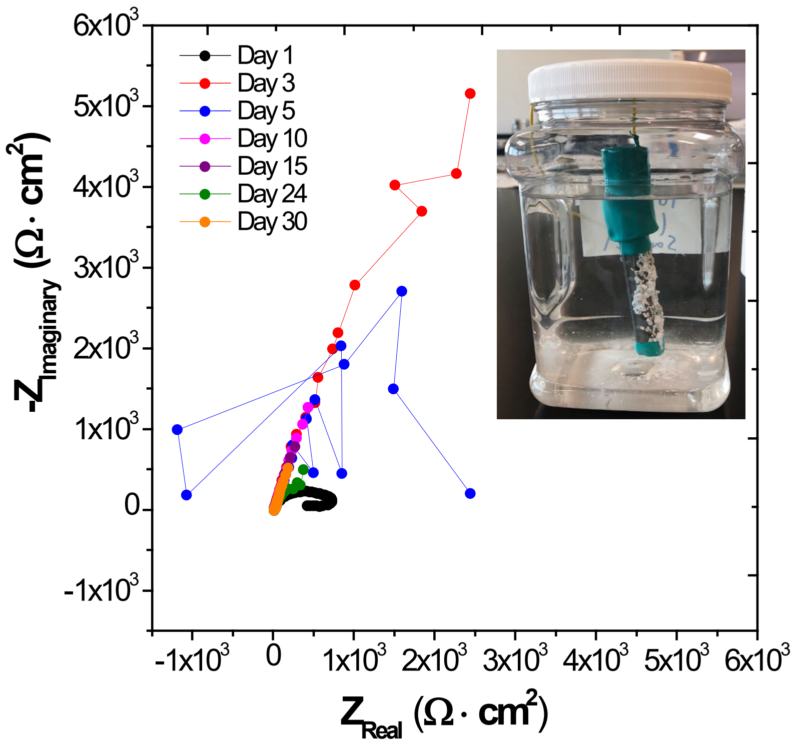


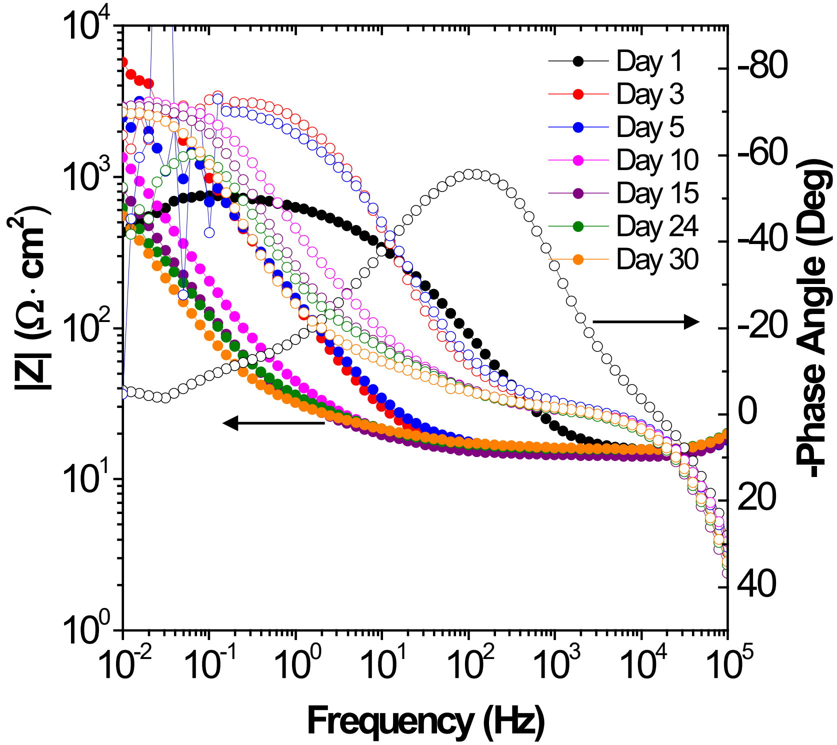


Impedance decreased gradually with immersion time suggesting zinc dissolution that provided sacrificial protection to the steel rebar

Continuous Immersion Test

EIS Results for 1035(2) Sample





The impedance increased for the first three days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

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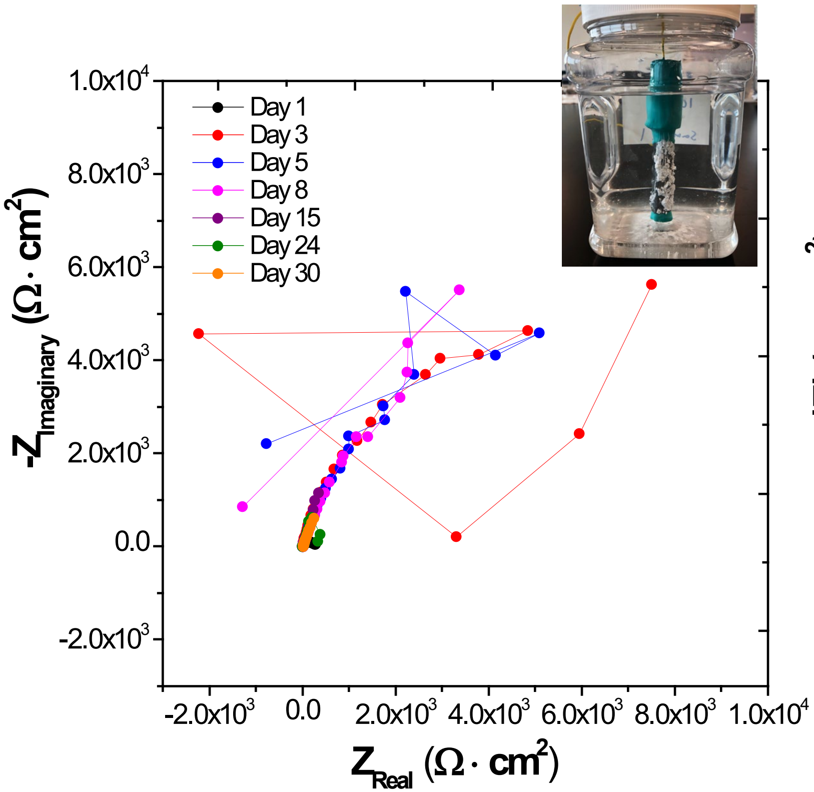
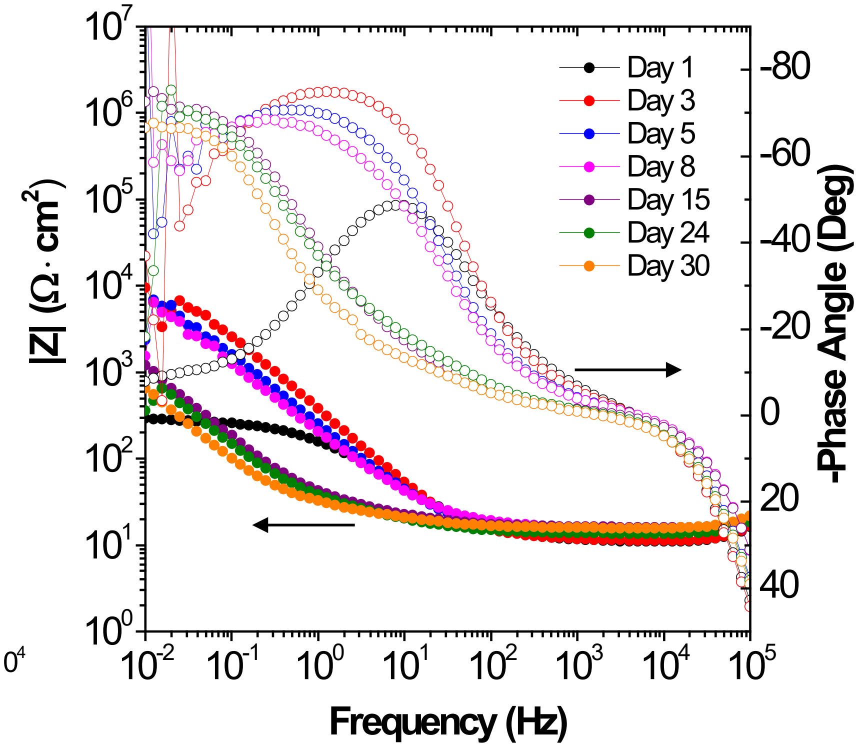
EIS Results for 1035(4) Sample





The impedance increased for the first eight days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

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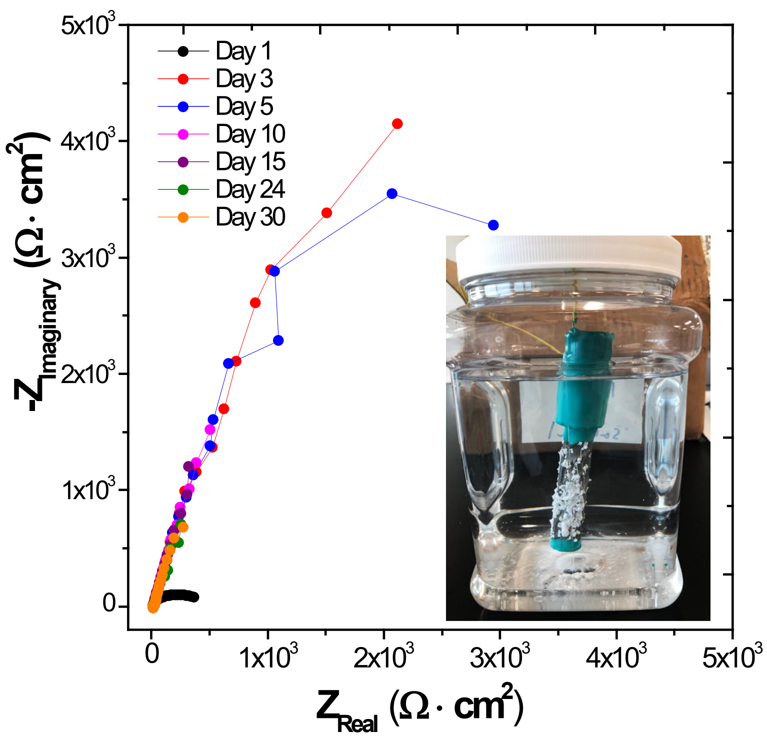
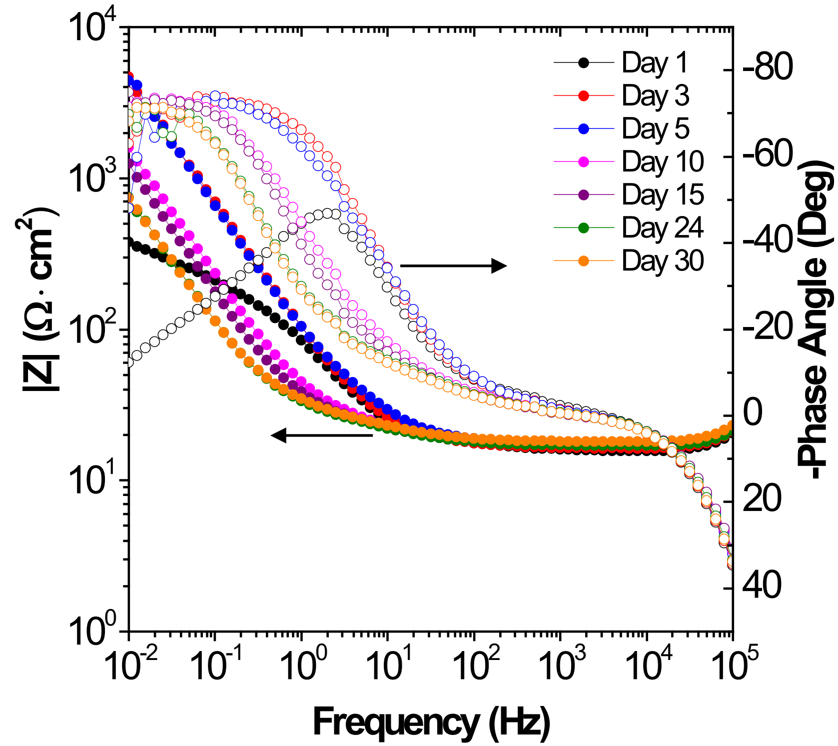
EIS Results for 1035(9) Sample





The impedance increased for the first five days (formation of zinc corrosion products) but then it decreased with further immersion time (zinc reactivation)

Continuous Immersion Test

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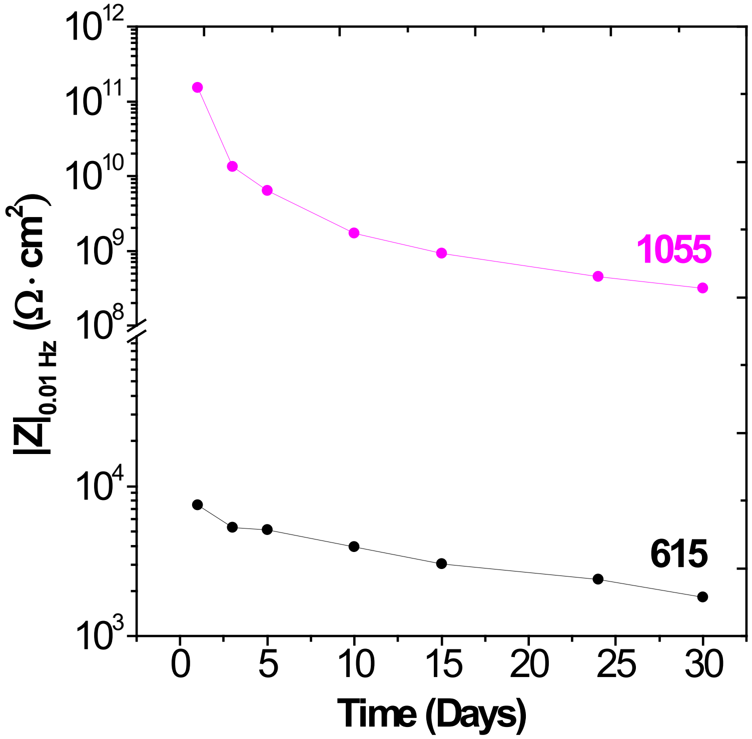
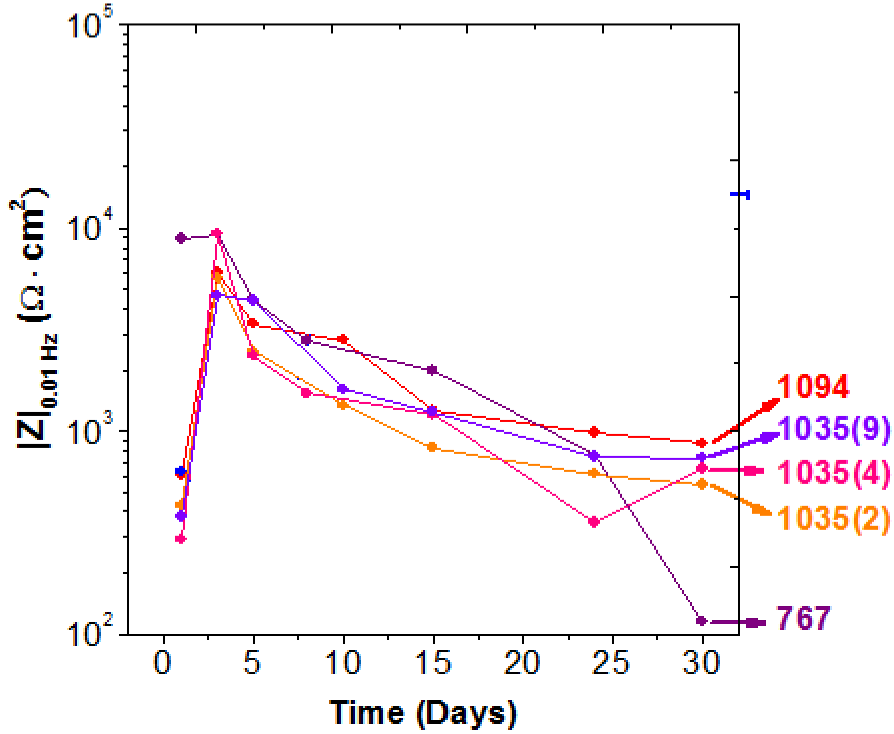
TOTAL IMPEDANCE





Cyclic Fog Chamber Test

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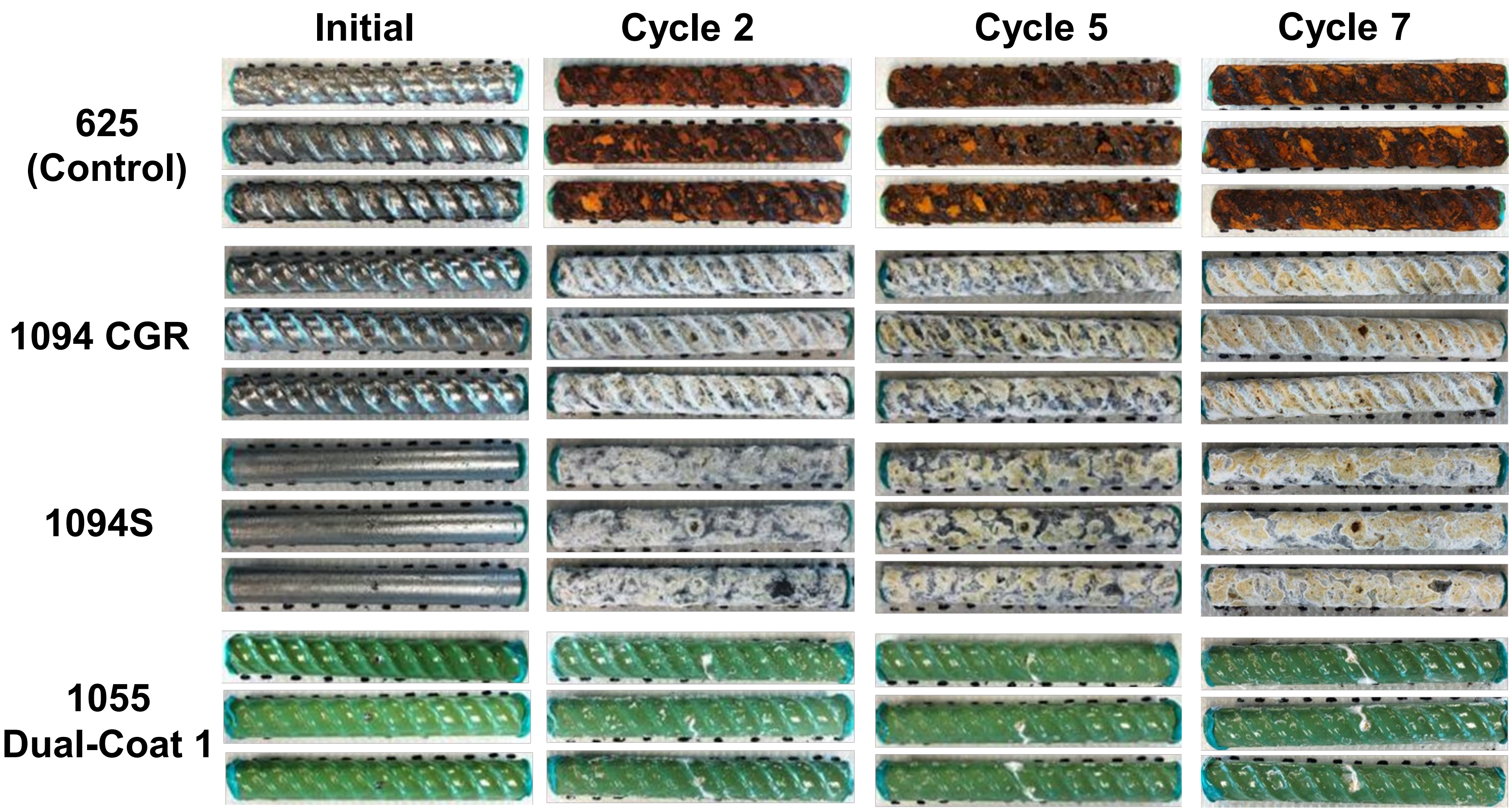

Cyclic Fog Chamber Test

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Initial | Cycle 2 | Cycle 5 | Cycle 7

Uniform corrosion

625 (Control)

Sacrificial protection but with sign of rebar corrosion

1094 CGR

Sacrificial protection but with sign of rebar corrosion

1094S

Effective barrier protection and sacrificial protection for defect

1055 Dual-Coat 1

Cyclic Fog Chamber Test

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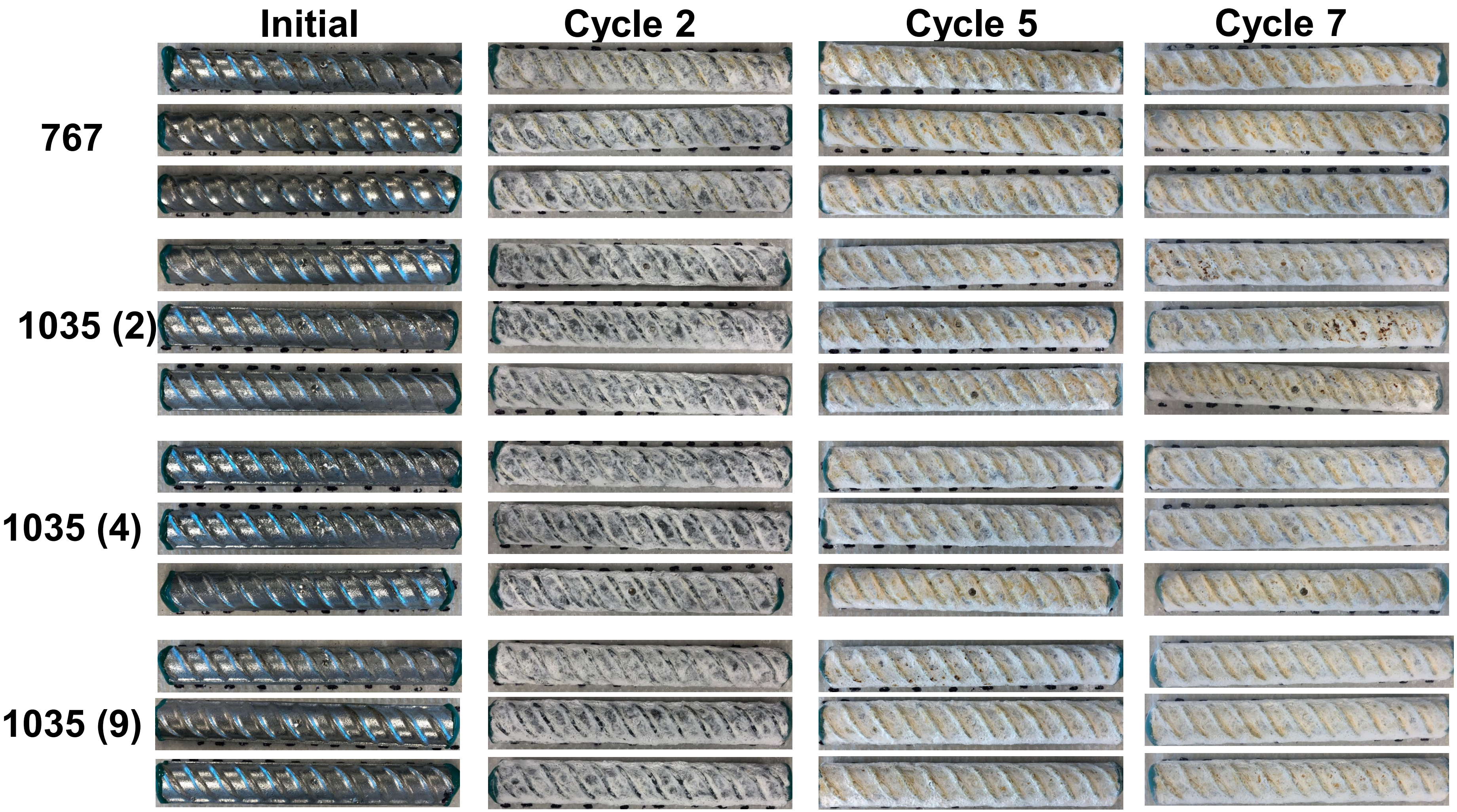


Cyclic Fog Chamber Test

Initial | Cycle 2 | Cycle 5 | Cycle 7

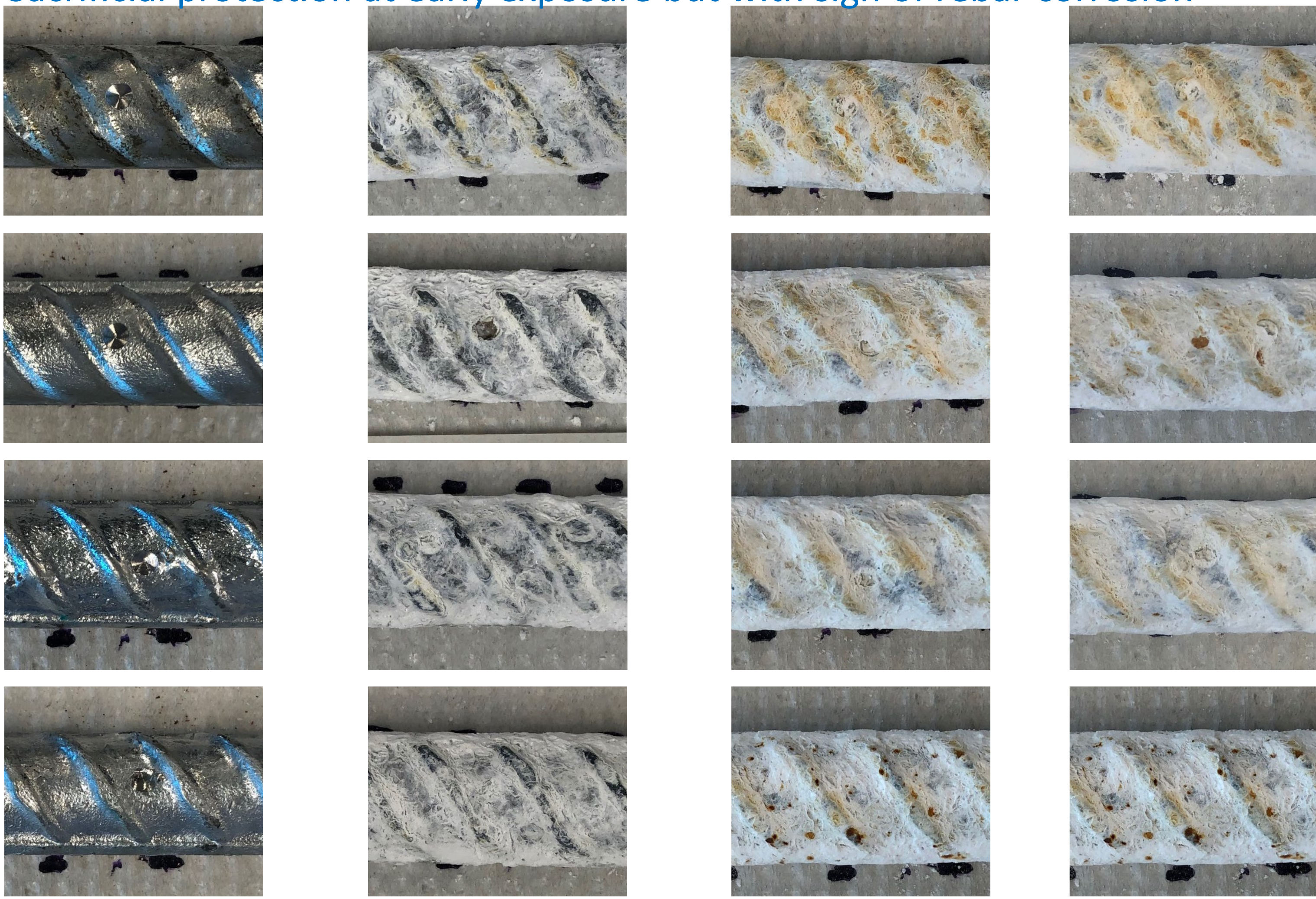
Sacrificial protection at early exposure but with sign of rebar corrosion

767

1035 (2)

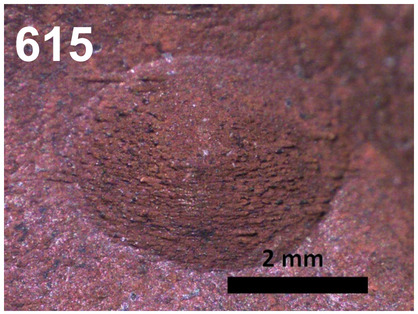
1035 (4)

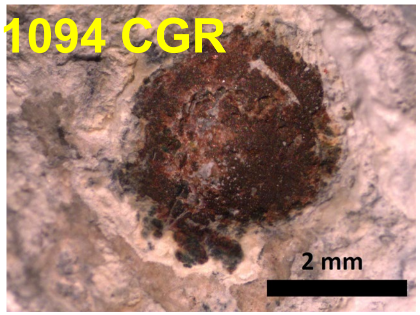
1035 (9)

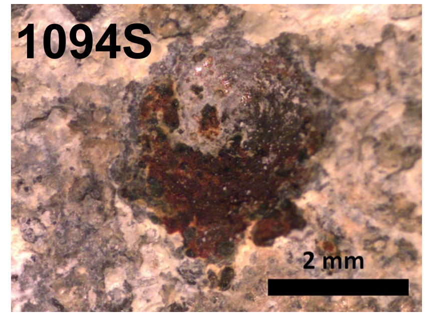


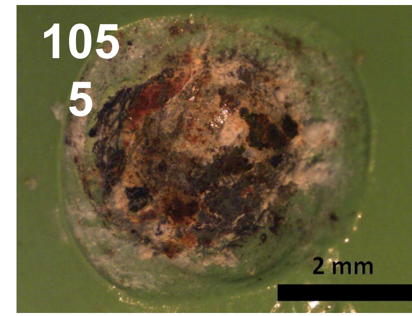
Cyclic Fog Chamber Test

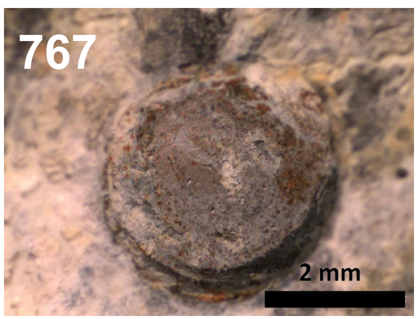
Stereo Microscope Images

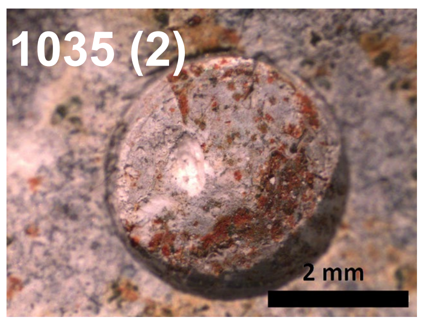


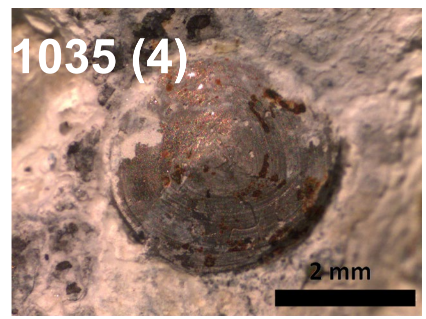


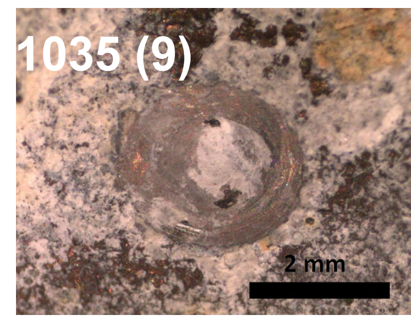


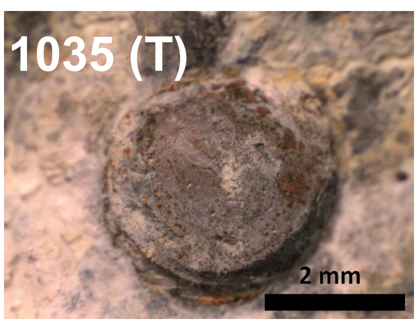












Future Work

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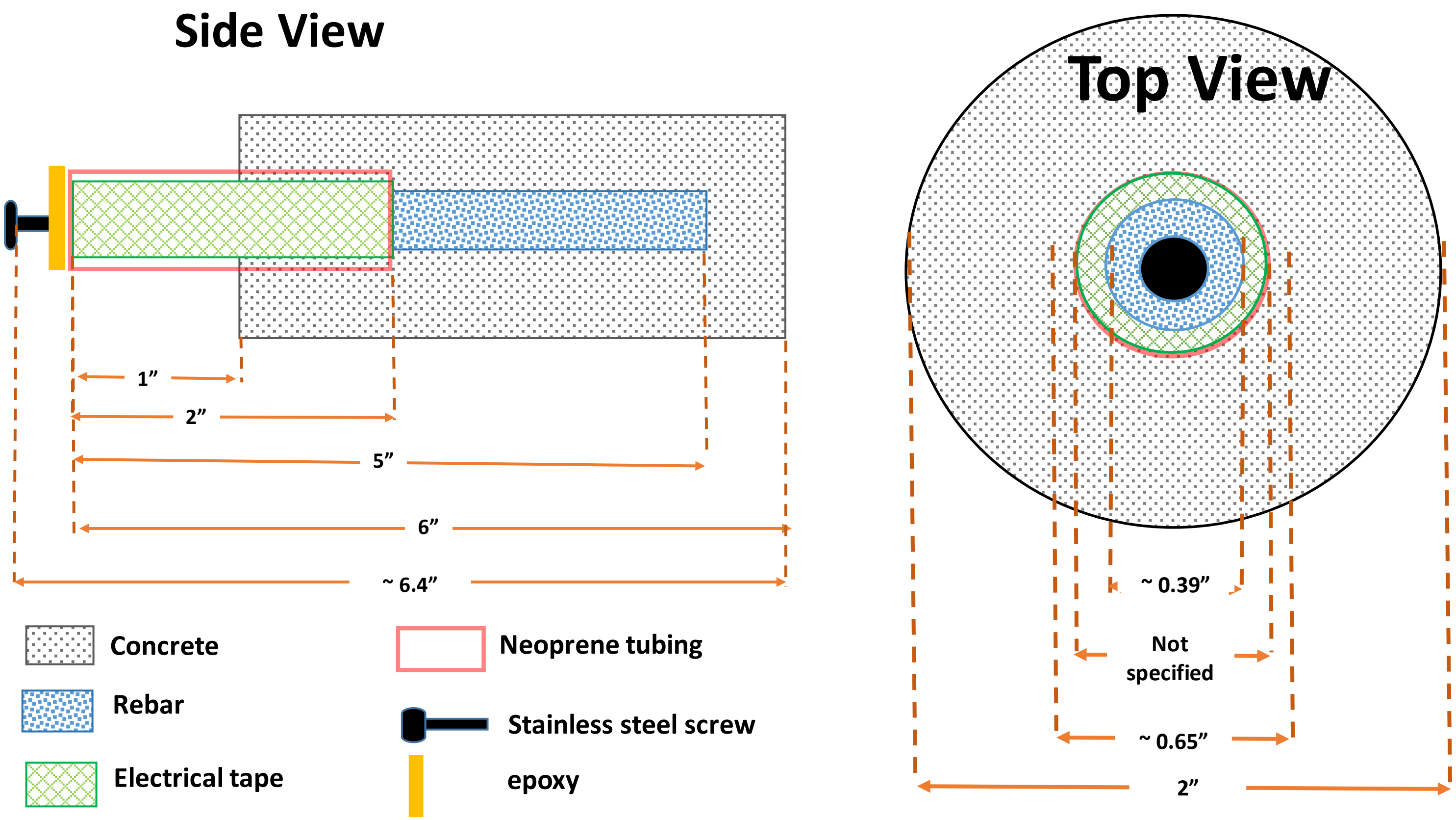
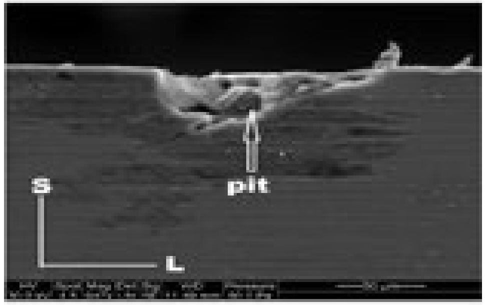
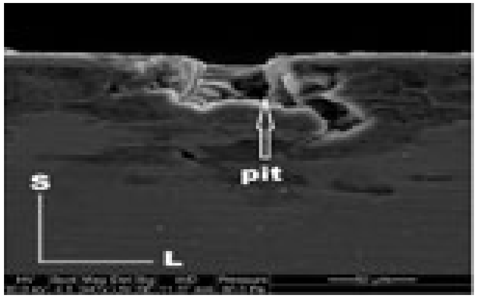
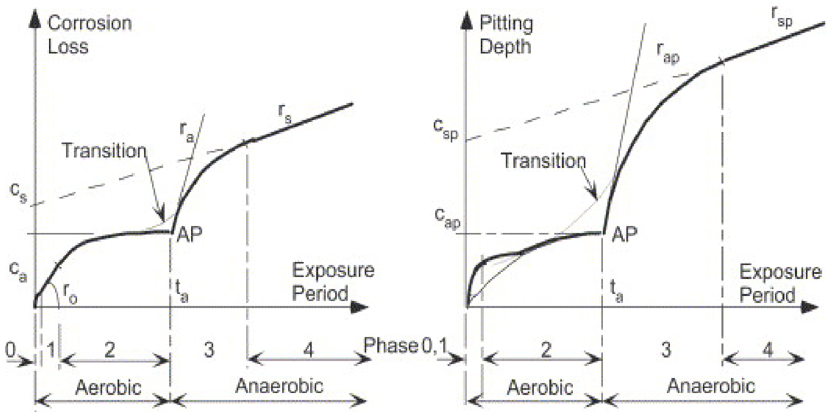
Accelerated and Immersion Test using reinforced concrete samples

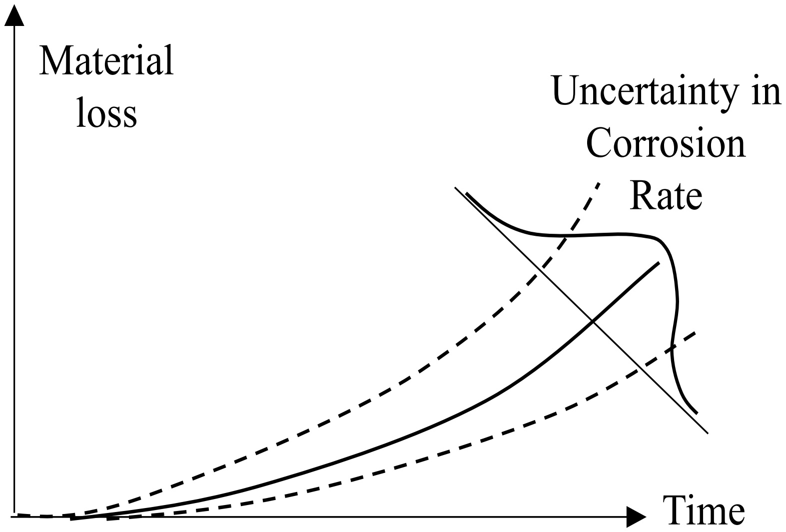


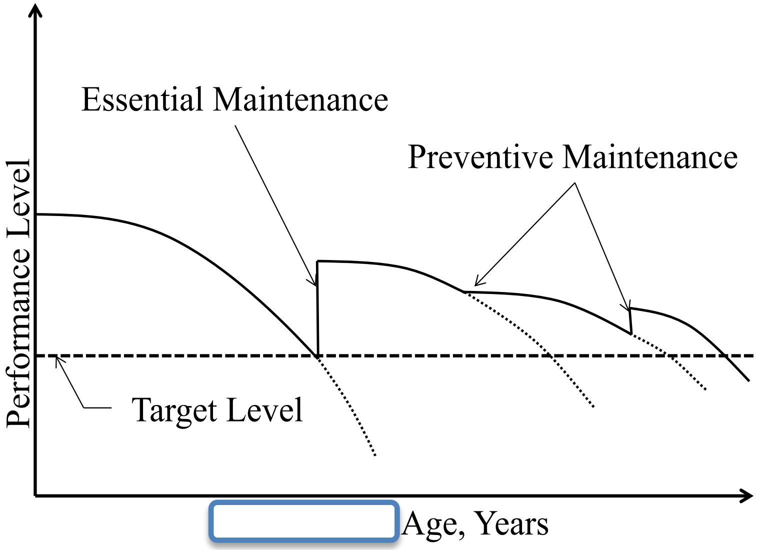
Reliability Modeling











Lifetime target

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- Corrosion protection and performance
  – 45 + years
  Demonstrated
  – 60 + years
  Additional Expected
  – ***105 + years***
  Remaining
  Service life

TEXAS A&M ENGINEERING
EXPERIMENT STATION

The Future of Galvanized Rebar and Continuous Galvanized Product Innovations

Mike Stroia

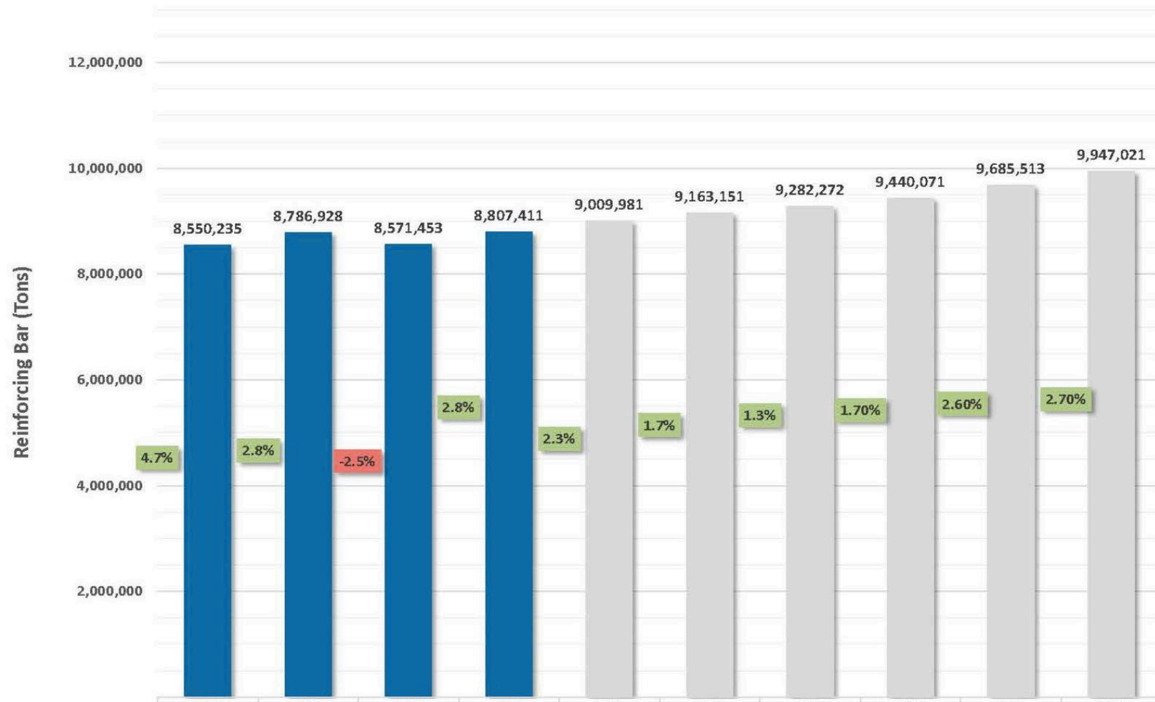
GalvaBar

2019 TRAN-SET-CIR-AZZ Symposium

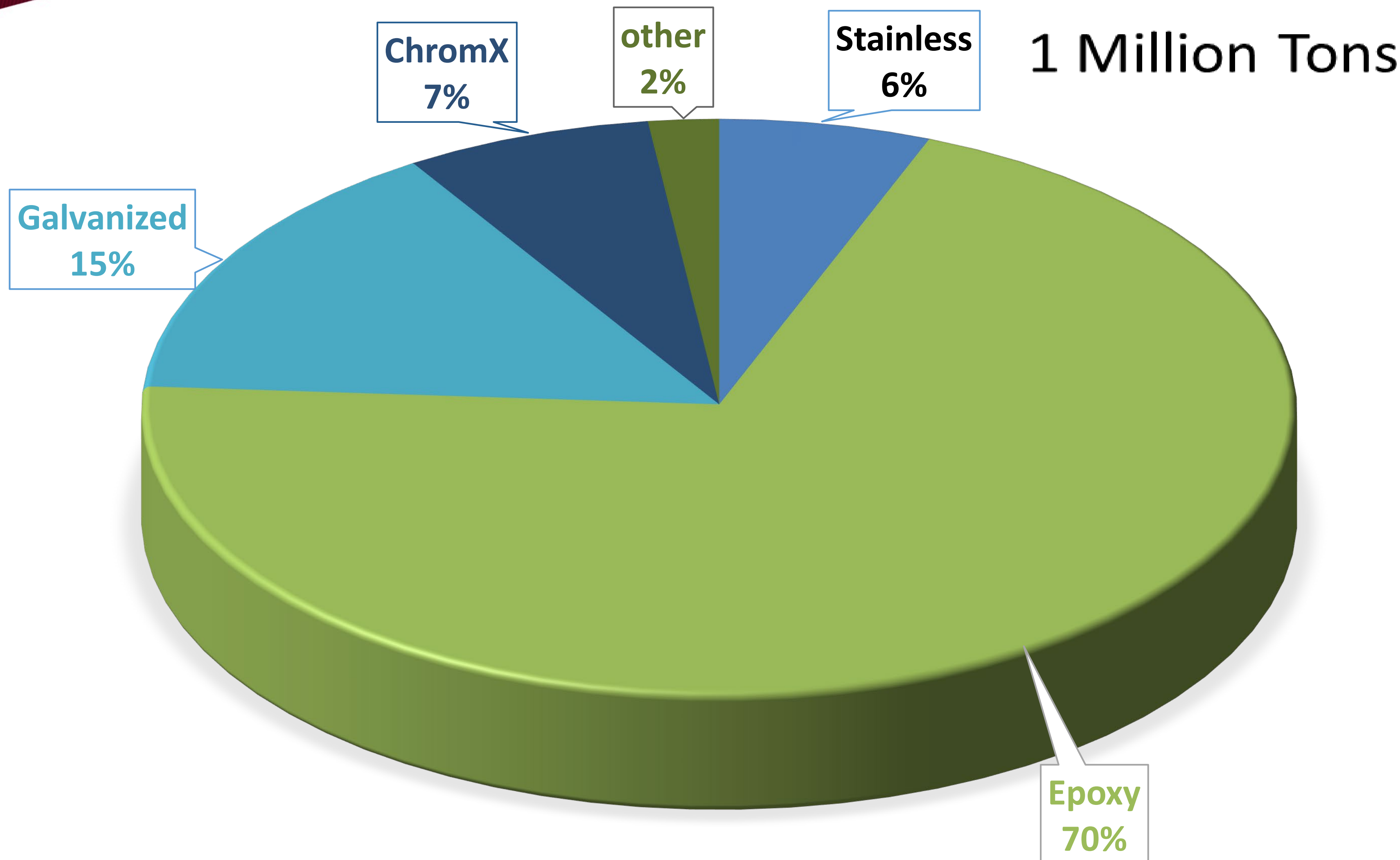
August 28, 2019

This Seminar is a look forward at existing dual coat technologies that can lower the total cost of ownership for the life of structures while providing a 100+ year life. Continuous galvanized rebar can be used as a substrate for epoxy coatings or can be used as an additional barrier coating for ChromX steels. These technologies can provide the life of Stainless Steel rebar at a lower cost to owners.

CRSI Reinforcing Bar Forecast – USA Total



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Reinforcing Bar (SMA)	8,550,235	8,786,928	8,571,453	8,807,411						
Growth Rates (SMA)	4.7%	2.8%	-2.5%	2.8%						
Reinforcing Bar (PCA)					9,009,981	9,163,151	9,282,272	9,440,071	9,685,513	9,947,021
Growth Rates (PCA)					2.3%	1.7%	1.3%	1.70%	2.60%	2.70%
Reinforcing Bar (Dodge)					8,807,411					
Growth Rates (Dodge)					0%					



CORROSION RESISTANT REBAR MARKET %

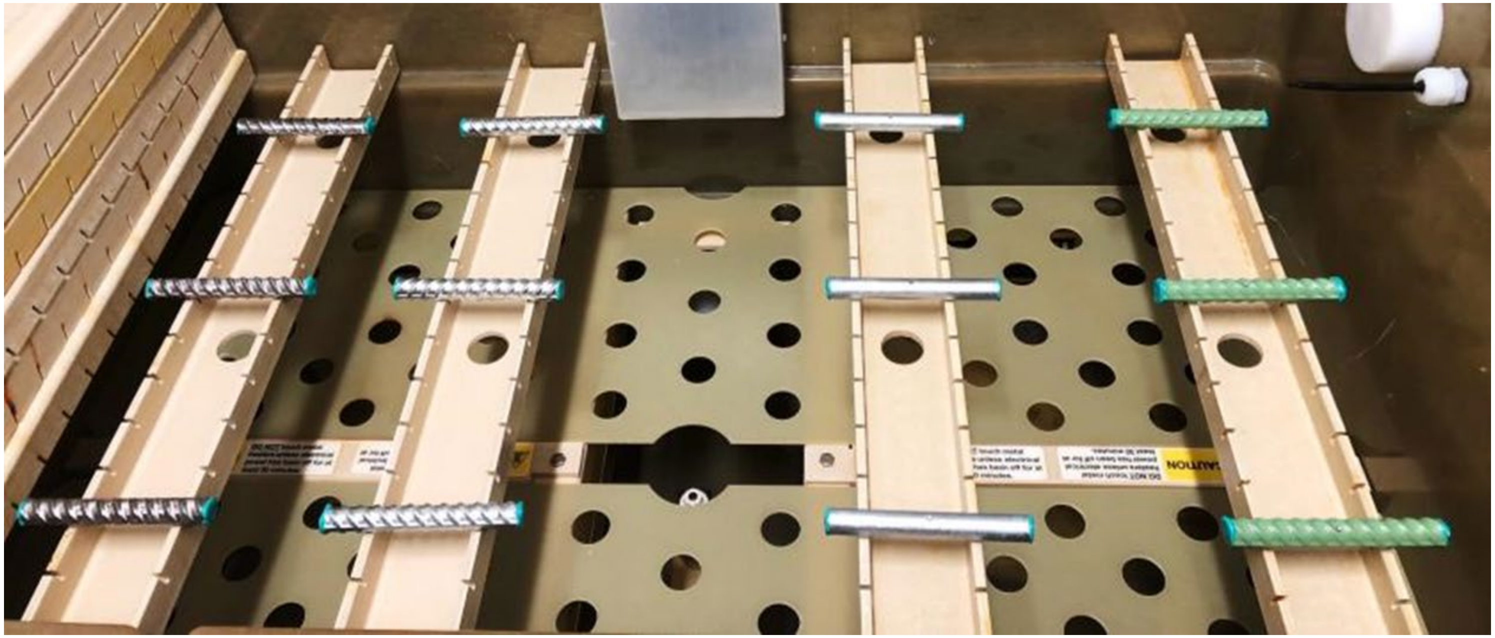
A767

A1094

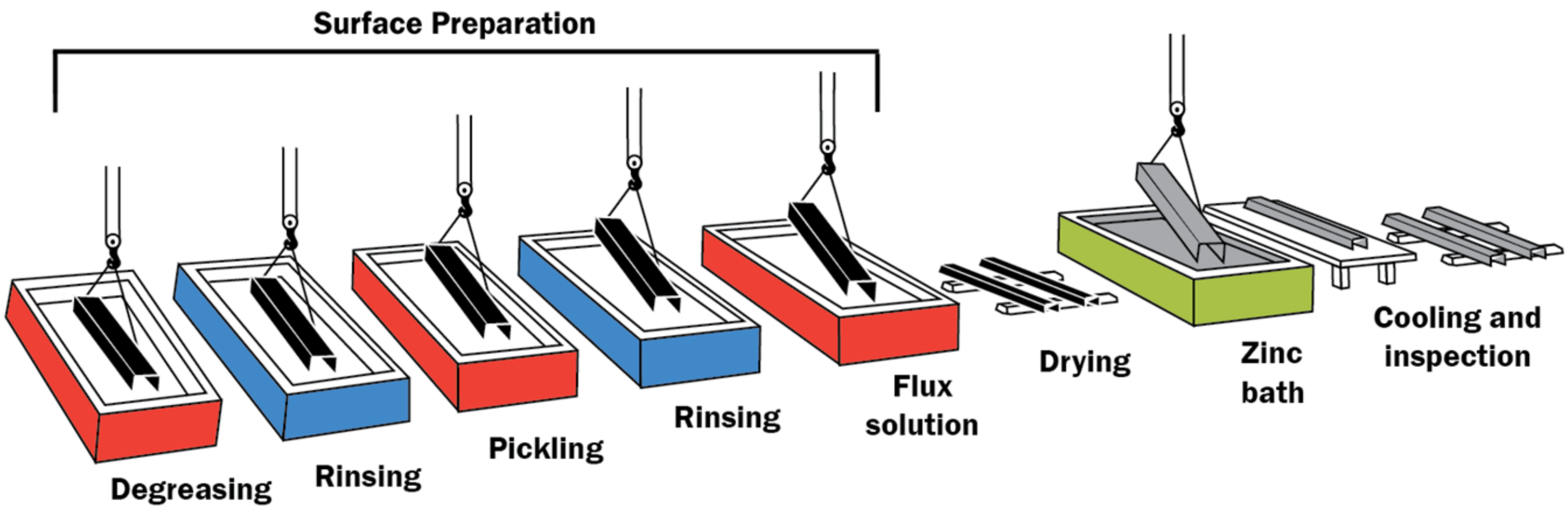
- Smooth- Dowel
- A1035 Deformed
- A1035 Post Tensioned Threaded

A1055

- Utilizing Type 2 Continuous galvanized rebar/ A775 Epoxy Coating
- *A934 Epoxy Coating (cages/ welded items)



ASTM A767 Hot-dip Galvanized Rebar



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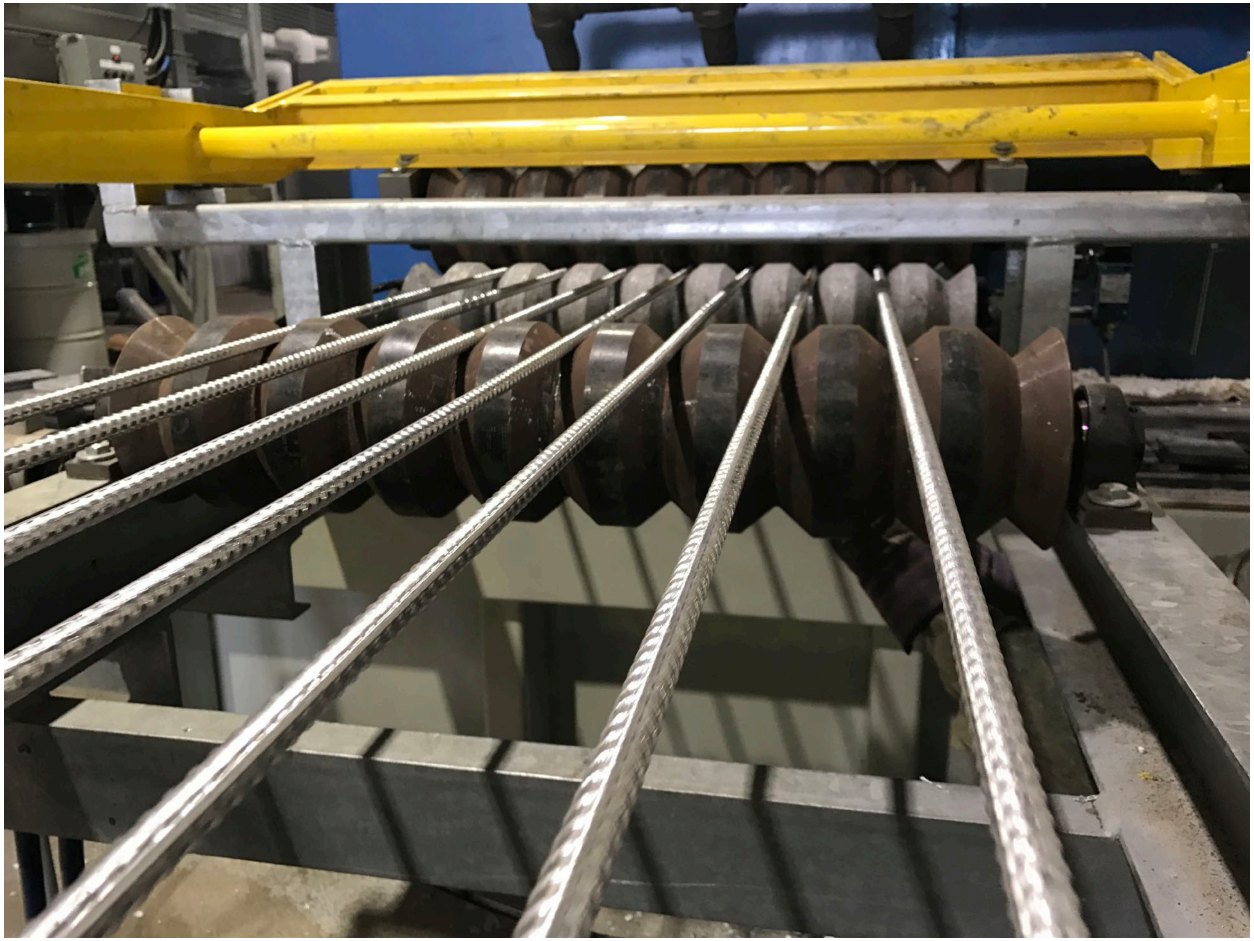
ASTM A1094 Continuous Hot-Dip Galvanized

- Rebar
- Smooth - Dowels



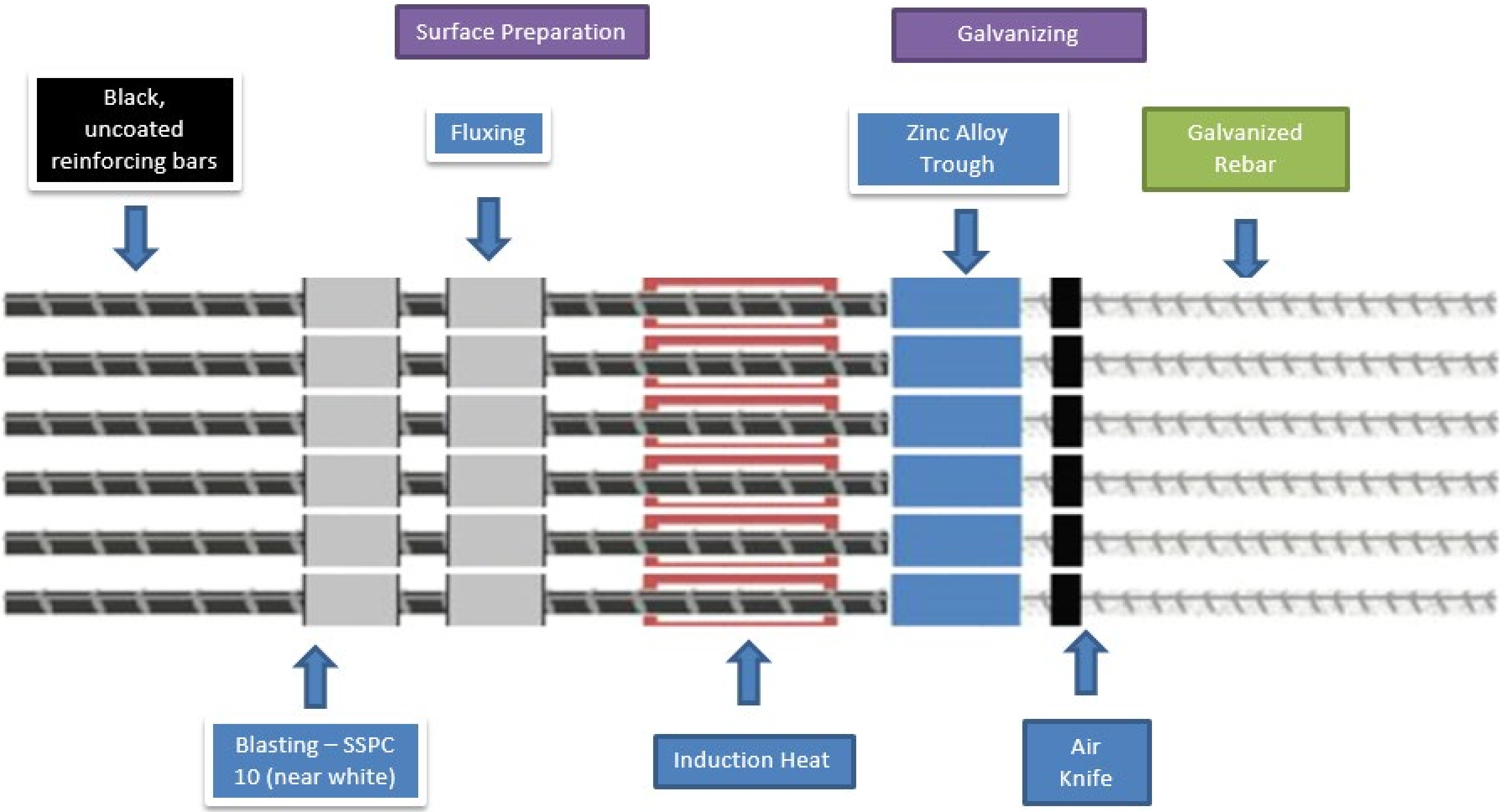
Proven Protection + Innovative Processing

Utilization of current supply chains. Steel Mills, Independent Fabricators, Distribution

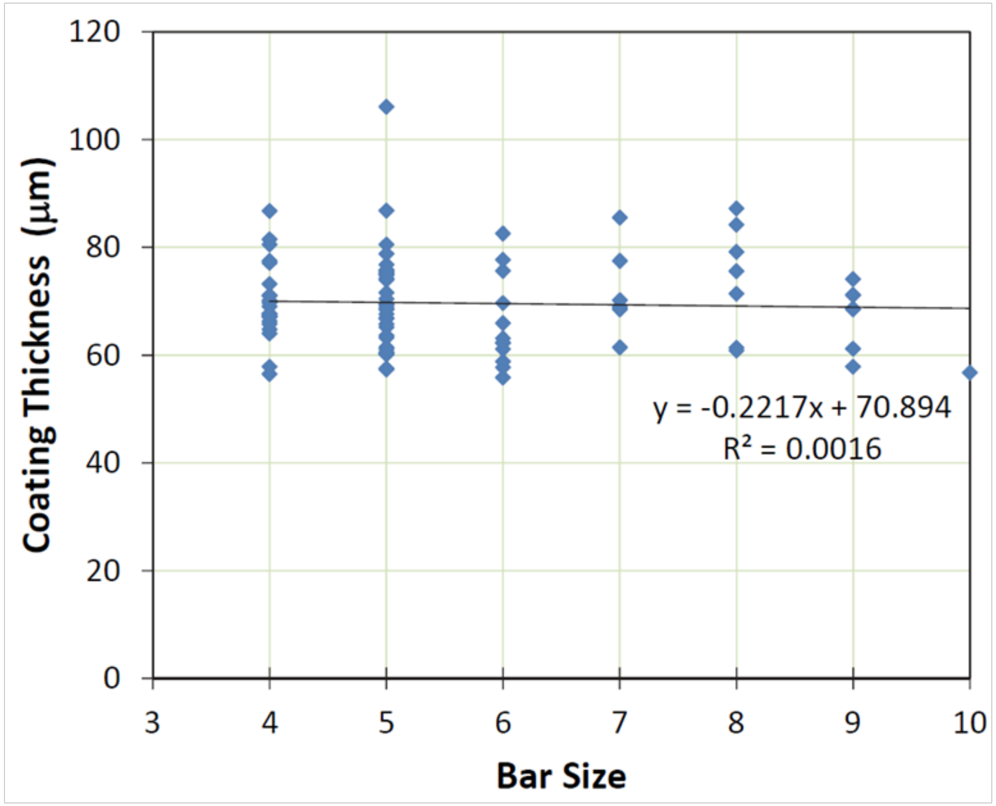
Rebar can be staged in stock lengths prior to being released by fabrication creating a consistent flow of product and allowing for field changes to be addressed on the fly

No special equipment or special handling. Utilize the most efficient machinery

Seamless supply of GalvaBar to projects through current supply chain without double handling resulting in better product flow and customer satisfaction.


Surface Preparation
Galvanizing
Black, uncoated reinforcing bars
Fluxing
Zinc Alloy Trough
Galvanized Rebar
Blasting – SSPC 10 (near white)
Induction Heat
Air Knife

Consistent Coating Thickness



- Statistics shows that rebars of different sizes (#4 to #10) produced had consistent coating thickness.
- The correlation between coating thickness and rebar size was almost perfectly zero (R^2 = 0.0016).
- That allows us to treat the data across the bar sizes as one single group.

ASTM A1035 ChromX/ CGR

- 2100
- 4100
- 9100

Corrosion resistant black bar with a continuous galvanized coating.

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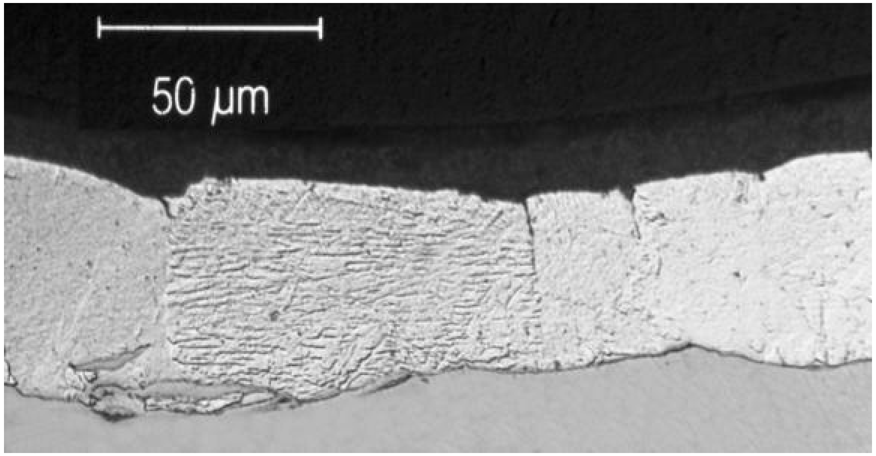
A1055

Utilizing Type 2 Continuous galvanized rebar

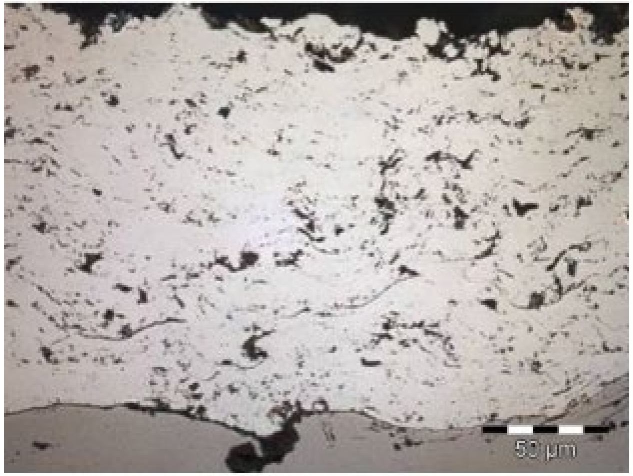
A775 Epoxy Coating

VS

ASTM A1055 Type 1 vs Type 2

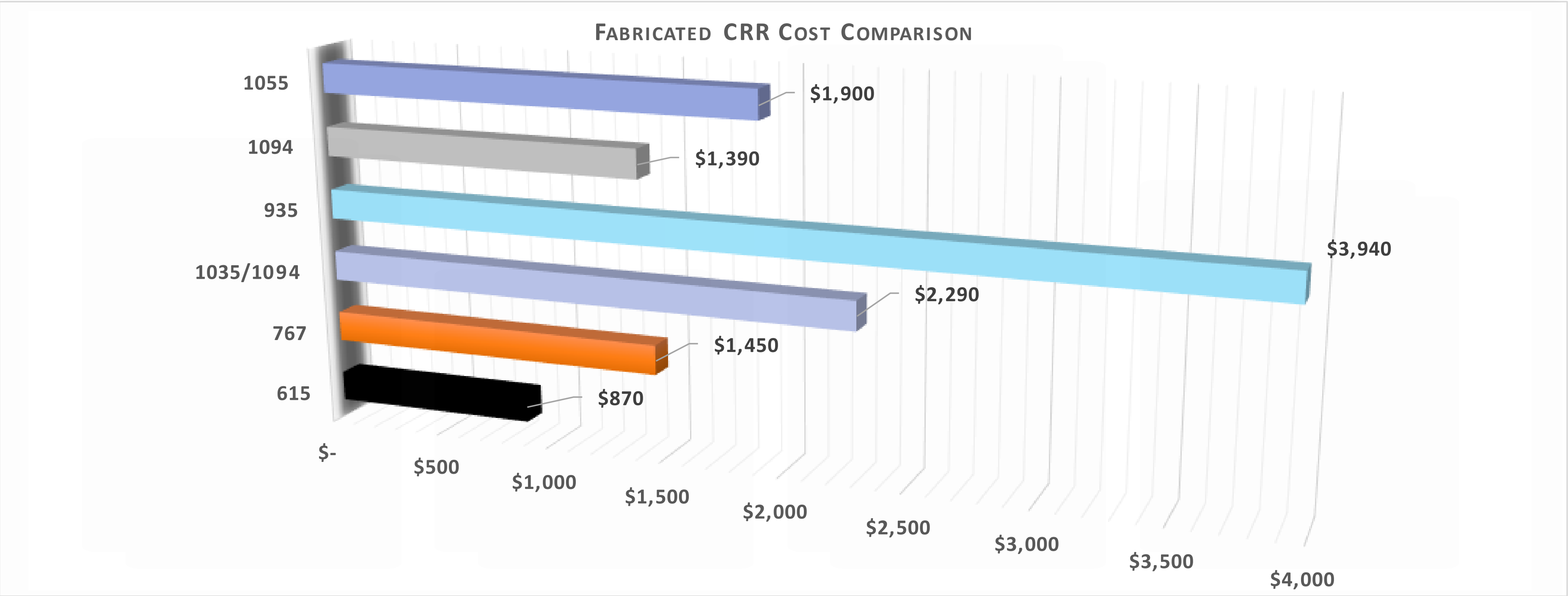


CGR Zinc Coating 2 mil/ 50 Micron min

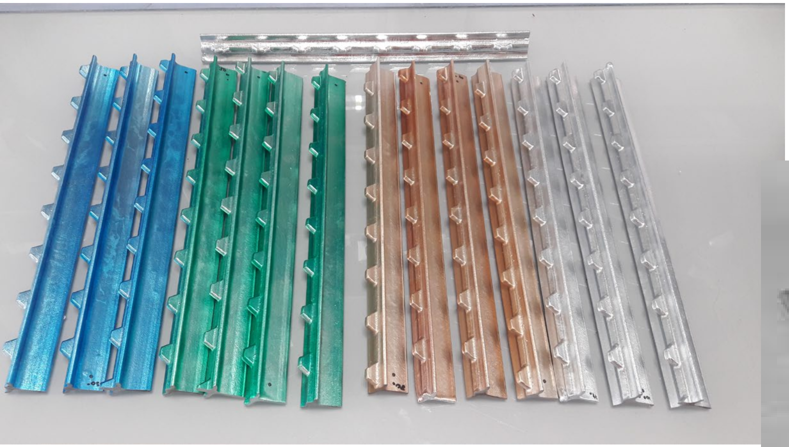


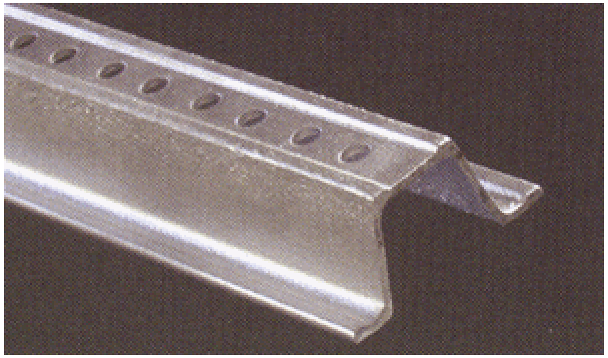
Thermal Spray Zinc 1.4 mil/
35 micron min

Fabricated Corrosion Resistant Rebar $/ Ton



OTHER PRODUCTS





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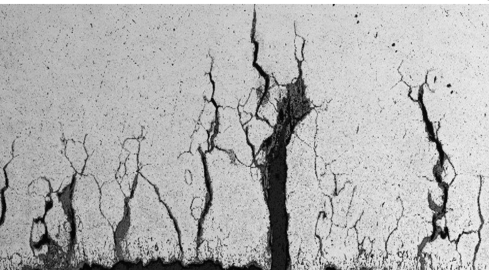
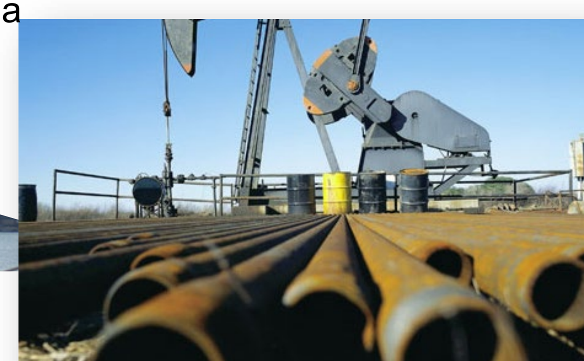


Corrosion Research Consortia

Consortia Concept for Infrastructure Topics (Corrosion)

H. Castaneda



Why infrastructure?

1. The industry's only **corrosion-related consortia** administered by one of the premier global corrosion engineering laboratories is seeking corrosion science and engineering experts to collaborate in a neutral forum for researching innovative solutions to key challenges faced by the infrastructure industry.

2. A large bridge inventory of over 610,000 bridges in the US requires routine inspection and maintenance. A significant portion of this inventory is subjected to corrosive precursors in the environment. Consequently, corrosion-induced damages to structural elements are one of the leading causes for damage, which consumes an enormous amount of annual budget for bridge maintenance, repair, inspection, and replacement.

Concept

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- Various industries have substantive corrosion-related issues and need to invest in research to understand how to best mitigate corrosion in their assets.
- Decreased corporate investment in research, however, slows if not halts many from getting this vital information.
- Consortia can assist organizations, universities, and government entities in funding, administering, and attaining research.
- By offering services and brokering relationships between organizations, a consortia provides for industry partners to pool their resources to study and share in the results of research pertinent to them.

Concept (cont.)

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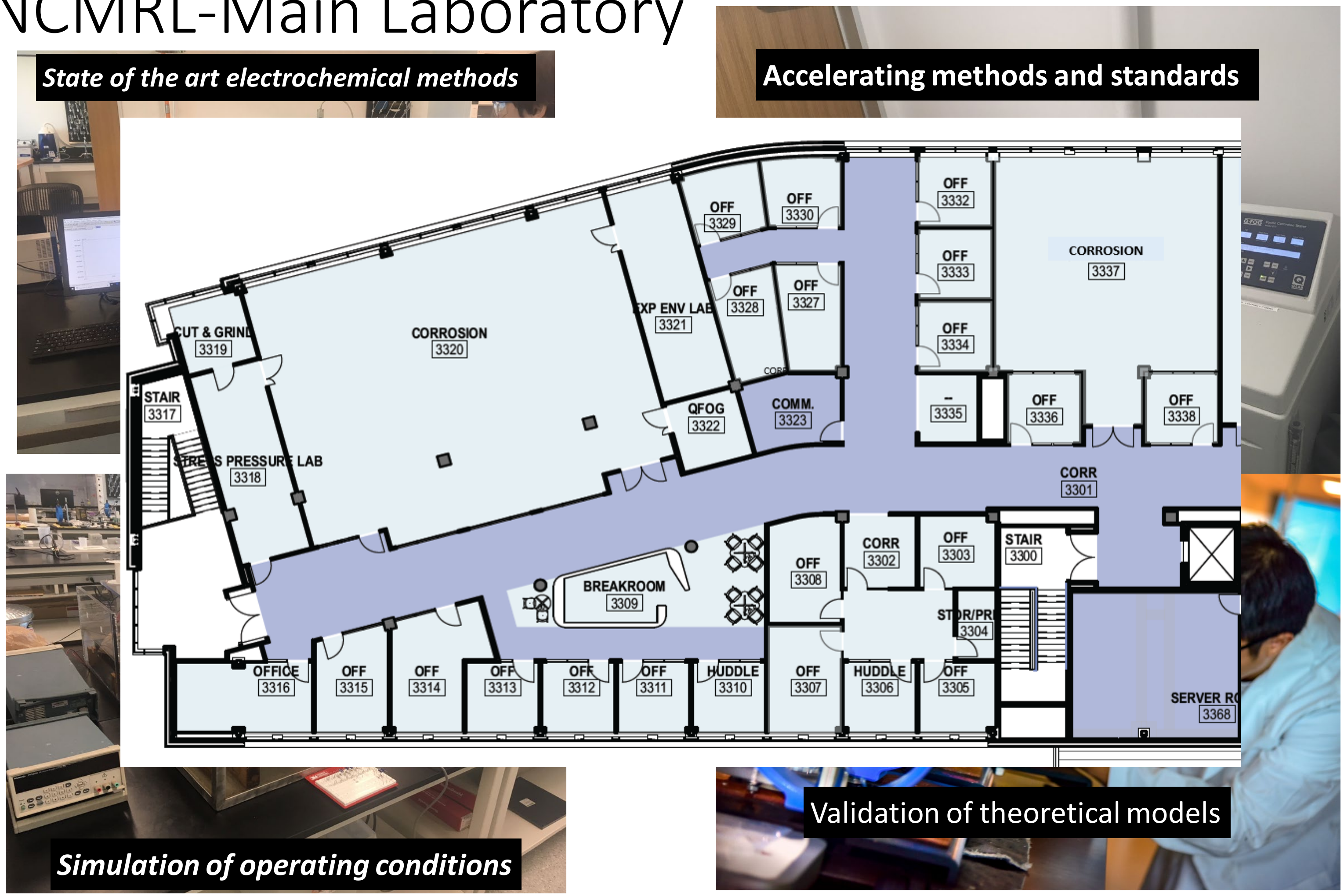
- **Texas A&M/NCMRL** will bring two or more organizations together to collaborate on new research in various industries seeking to mitigate corrosion.
  - Sharing costs to study a technical area.
  - Consortia members will formalize the overall structure and scope of the project while…
  - NCMRL supplies administrative services and brokers the consortia relationships to facilitate the research.
  - Consortia members will likewise share in the results and receive access to the research — before it is available to the public.

WHY participate in Corrosion/Infrastructure Consortia?

- ✓ While other consortia may have a corrosion component, NCMRL uniquely offers a specific, in-depth focus on corrosion.
- ✓ With its long history of developing technical knowledge in corrosion prevention and extending the life of assets, NCMRL is ideally positioned to lead and broker partnerships for the distribution of new research.

NCMRL is committed to establish a strong partnership with the industry and the leader institutions on corrosion control and materials reliability

NCMRL-Main Laboratory



Membership Levels

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- Membership Levels
  - Strategic member
  - Technical Committee Member
  - Advisory member

Strategic Member	Technical Committee Member	Advisory Member
$30,000	$15,000	$8,000

Strategic member

- Guide consortium development and select thematic research projects
- Short courses and symposia attendance (certified courses)
- Resources for recruiting well-trained graduates through co-op/intern programs and interaction with consortium personnel
- Access to basic and apply research generated

- Development of Test Methods
- Technology transfer for Understanding the degradation mechanisms of the substrate/coating/environment
- Access to computer based models
- Access to monitoring methodologies

Benefits

- High tech research value based on the scope of the consortia
- Documentation (reports, proceedings, papers, methods, standards)
- Technology transfers (basic courses)
- Discussion forums (workshops and seminars)

Next Steps

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- Forming committee to shape and review scope of work.
  - Based upon companies that are interested in participating

- Committee recommends Governance final draft for approval by all members.

- Proposed start date: Spring 2020

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Questions?