Case Studies for 125-Year Service Life Utilizing High Strength Low Chromium Reinforcing Bars

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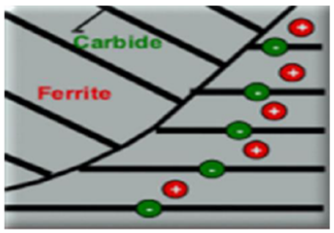
Presentation Overview

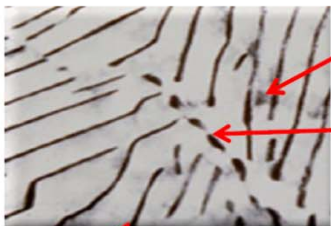
- ASTM A1035 Low Chromium Alloys
- Corrosion Performance of Low Chromium Alloys
- Chloride Threshold Levels for Low Chromium Alloys
- Definition of service life
- Importance of designing for service life
- STADIUM® Model for estimating/predicting service life
- Comparing results for bridge decks and marine piles for Low Chromium Alloys versus black bar (BB) and stainless steel bar (SS)

Microstructure of BB vs. A1035 Bars

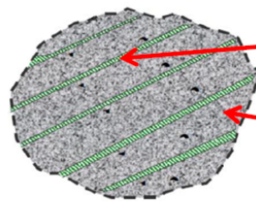
Typical Steel Microstructure

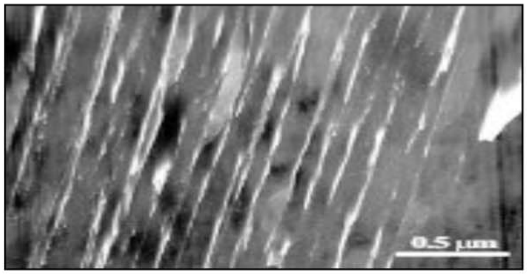


- Mild steel's microstructure is a mix of ferrite and iron carbide
- Together in the presence of moisture, chlorides & oxygen, the ferrite and iron carbide form galvanic cells (like batteries), which accelerate the process of corrosion from the inside out



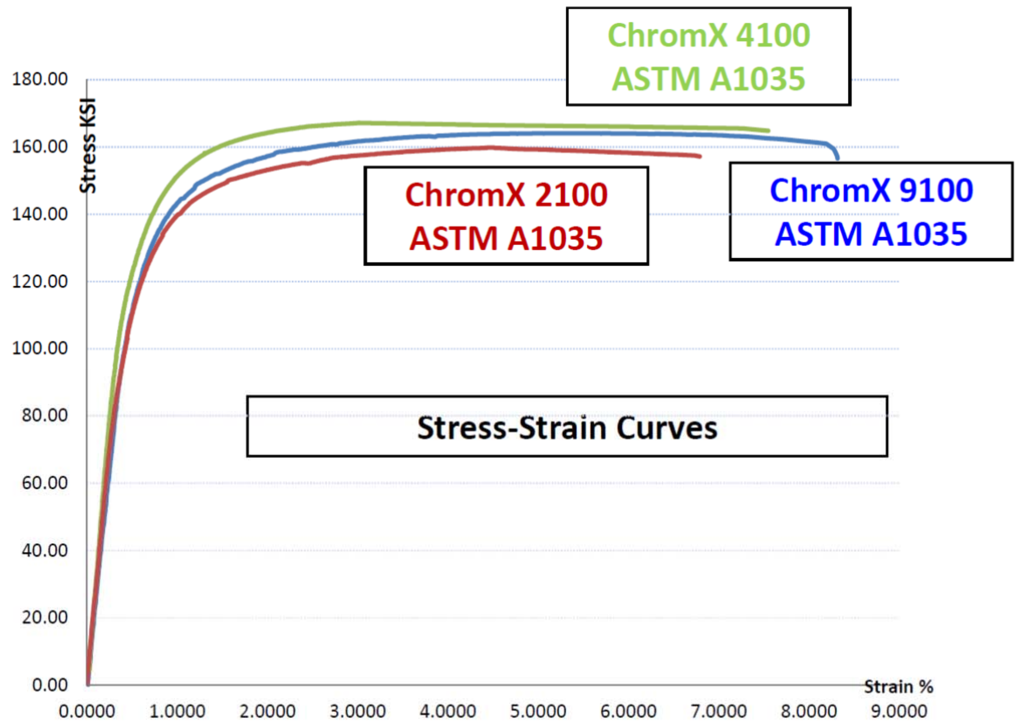
ChrōmX Microstructure





ChrōmX lamellar structure of martensite and retained austenite achieves high strength with ductility

Mechanical Properties



According to ASTM:

Yield strengths determined by **0.2%** offset method.

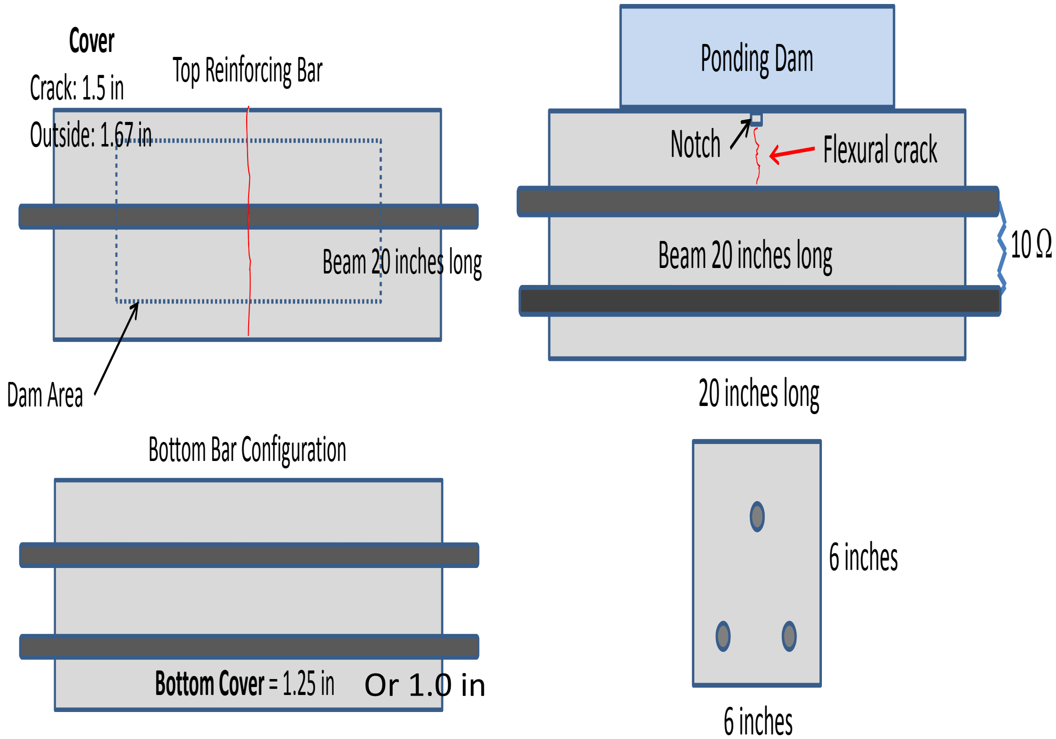
Corrosion Testing

- Cracked Beam Tests
- Lollipop Tests (not discussed due to time constraints, but results incorporated into threshold value determination)

Cracked Beam Macrocell Test

- 0.4 w/c, ¾-in nominal aggregate
- 1.5-in cover over the crack location (bottom of notch)
- Beam Size 20 x 6 x 6-in with one #4 top bar and 2 #4 bottom bars for cathodes
- Bar end treatments—Will be far from salt water so will remain dry.
  - Sealed shrink wrap in production and moist curing
  - Attach ground clamps to make electrical connections
  - Seal ground clamps with liquid electrical tape
- Unreinforced beams to determine flexural strength in third point load
- 0.008-0.01-in crack on top surface to be made and kept open with a spacer after fatigue—Prior experience it works
- Five low frequency fatigue cycles every 3 cycles at 75% of flexural strength
- One cycle is 1 week with 3% NaCl and 1 weeks ambient drying
- Macrocell corrosion
- Corrosion potential when ponded
- Corrosion potential when liquid removed
  - over crack
  - 3-in each side of crack

Macrocell Crack Beam Schematic



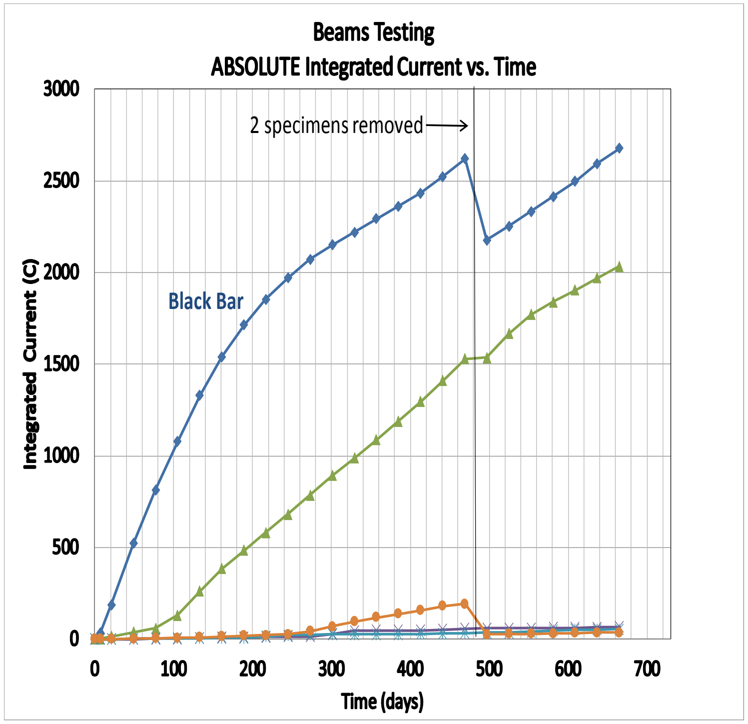
Bars Evaluated

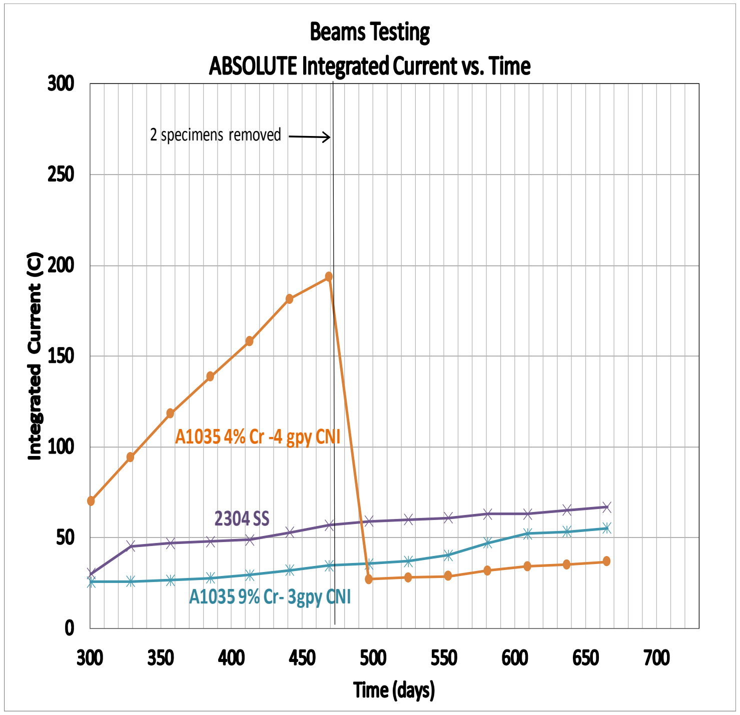
- Black Bar
- ASTM 1035-9% Cr
- ASTM 1035-9% Cr and 3 gpy Calcium Nitrite Inhibitor (CNI)
- ASTM 1035-4% Cr and 4 gpy CNI
- 2304 SS

Concrete Properties of Corrosion Specimens

Property/Material	BB, 1035-9Cr, S32304,	1035-9Cr 3CNI	1035-4Cr 4CNI
Cement (pcy)	658	658	658
w/c	0.4	0.4	0.4
CNI (gpy)	0	3	4
Air (%)	6.4	6.2	6.5
Slump (in.)	5.1	4.75	4
Compr. Str. (psi)			
1 day	2590	2800	2820
14 days	5490	7220	6740
28 days	6150	7755	7290
Flex. Str. (psi)			
14 days	770	800	750
28 days	880	850	830

Cracked Beam Integrated Macrocell Corrosion





ASTM A1035 Bar Appearance

A1035-9% Cr -3 Top Bar 492 Coulombs

A1035-9% Cr -3 Bottom Bar

A1035-9% Cr -5 Top Bar 2930 Coulombs

Top

Bot.

A1035-9% Cr -5 Bottom Bar

Chloride Profiles in Beams at 34 Cycles (68 Weeks)

Sample Location	Beam Description	Depth Increments in Inches					Beam Description	Depth Increments in Inches				
		0 to 1/2	1/2 to 1	1 to 1-1/2	1-1/2 to 2	2 to 2-1/2		0 to 1/2	1/2 to 1	1 to 1-1/2	1-1/2 to 2	2 to 2-1/2
1- Top Center Crack	A1035 4% Cr+4gpyCNI-12	5329	3673	2280	1740	1930	2304 SS-5	5292	3069	2493	2277	2273
2- Top Offset		4240	3487	2612	2564	2204		3143	1337	604	621	1003
3- Bottom Center Crack				1978						1676		
4- Bottom Offset				818						571		
1- Top Center Crack	A1035 4% Cr+4gpyCNI-15	5315	3045	2790	2276	2222	A1035 9% Cr-3	5130	3318	2635	2528	1777
2- Top Offset		2639	1111	694	637	493		3714	1414	670	653	721
3- Bottom Center Crack				1641						1247		
4- Bottom Offset				944						493		
1- Top Center Crack	A1035 9% Cr+3gpyCNI-11	4432	2676	2457	2306	1825	A1035 9% Cr-5	4404	2931	2344	2079	1687
2- Top Offset		3138	1377	614	634	718		3157	1257	666	574	727
3- Bottom Center Crack				832						1085		
4- Bottom Offset				662						732		
1- Top Center Crack	A1035 9% Cr+3gpyCNI-13	4404	2931	2344	2079	1687	BB-2	6526	4242	2872	2433	2337
2- Top Offset		3157	1257	666	574	727		4598	1942	726	654	561
3- Bottom Center Crack				1085						1668		
4- Bottom Offset				732						728		

Average Chlorides at 52 cycles (2 Years)

Bar	Top Center		Bottom Center	
	Average	SD	Average	SD
BB	3151	134	1561	67
4100	3371	227	1894	151
9100	2877	198	1668	58
4100 4gpy CNI	3165	289	1079	137
9100 3 gpy CNI	2822	275	1207	62
2304 SS	2930	235	1793	116
Sp		232		105
95% C.L.	330			150

Testing Conclusions

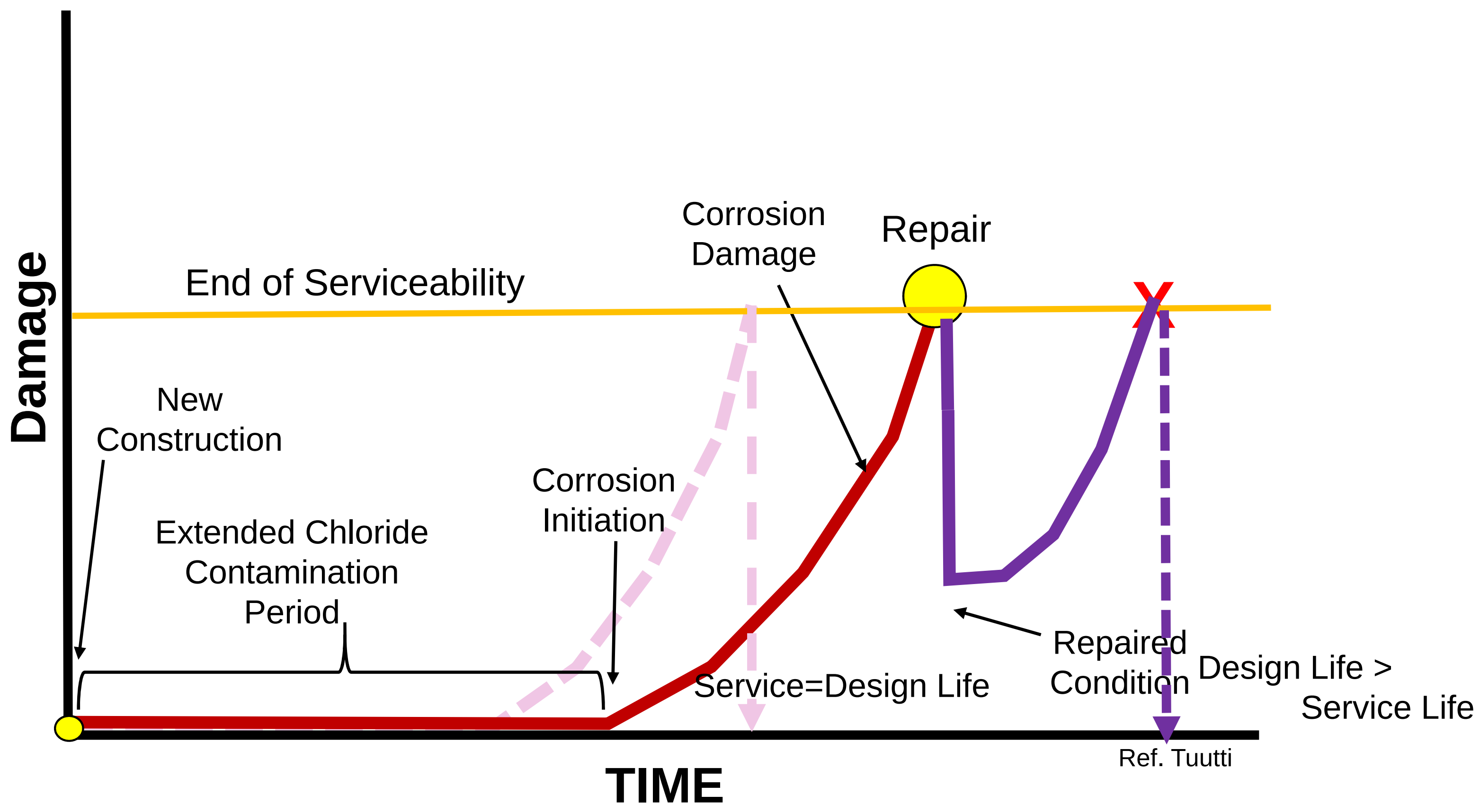
Severe corrosion testing of reinforcing bars in cracked and fatigued beams meeting minimum corrosion requirements showed that:

- A1035-9%Cr significantly outperformed black bar (BB)
- A1035-4% Cr and A1035-9% Cr with CNI had performance almost equivalent to 2304 SS even though the SS bars were pickled and the A1035 bars were tested with mill scale
- Chloride penetration to the bottom layer of steel was reduced with A1035 bars

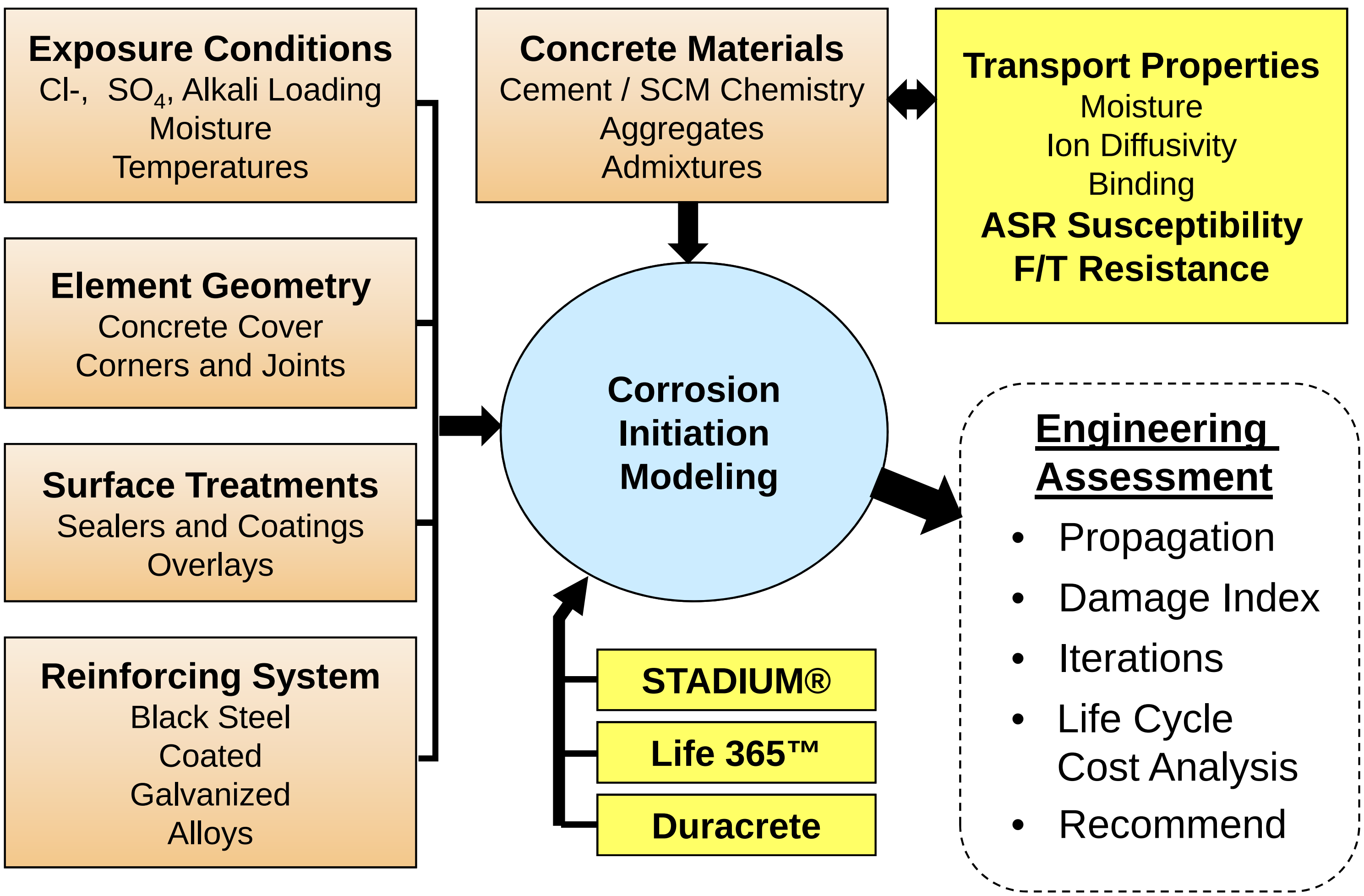
Service Life and Design Life

- Service Life is the time that a particular element of a structure or the structure as a whole is in use before major repairs are necessary.
  - Occasionally defined as time to corrosion initiation
  - Other alternative is to include the corrosion propagation time until repairs are required
  - In probability approaches the time is usually that at which 10 to 20% of the element/structure will need major repairs. Critical hard to repair elements will have a lower probability, while easily repaired elements could be at 20%.
- Design Life is how long the element or structure is expected to remain in use.
  - Can include multiple repairs
  - Often set at the service life
    - Repairs not practical or difficult to perform
    - Reduce overall life cycle cost of the structure

Tuuitti Model with Repair



Service Life Modeling Process



Threshold Values Used in Modeling

Bar Type	CNI Content (gpy)	Units	Base Value	Std. Dev.	CoV
BB	0	ppm	500	100	0.20
4100	0	ppm	1600	320	0.20
4100	2	ppm	2200	440	0.20
4100	3	ppm	2600	520	0.20
4100	4	ppm	3400	680	0.20
9100	0	ppm	2000	400	0.20
9100	2	ppm	2400	480	0.20
9100	3	ppm	2700	540	0.20
9100	4	ppm	3500	700	0.20
2304SS	-	ppm	3750	750	0.20
ECR	-	ppm	500	100	0.20
ECR 2-mats	-	ppm	900	180	0.20
HDG	-	ppm	1500	300	0.20

Case Study for Bridge Deck with Deicing Salts

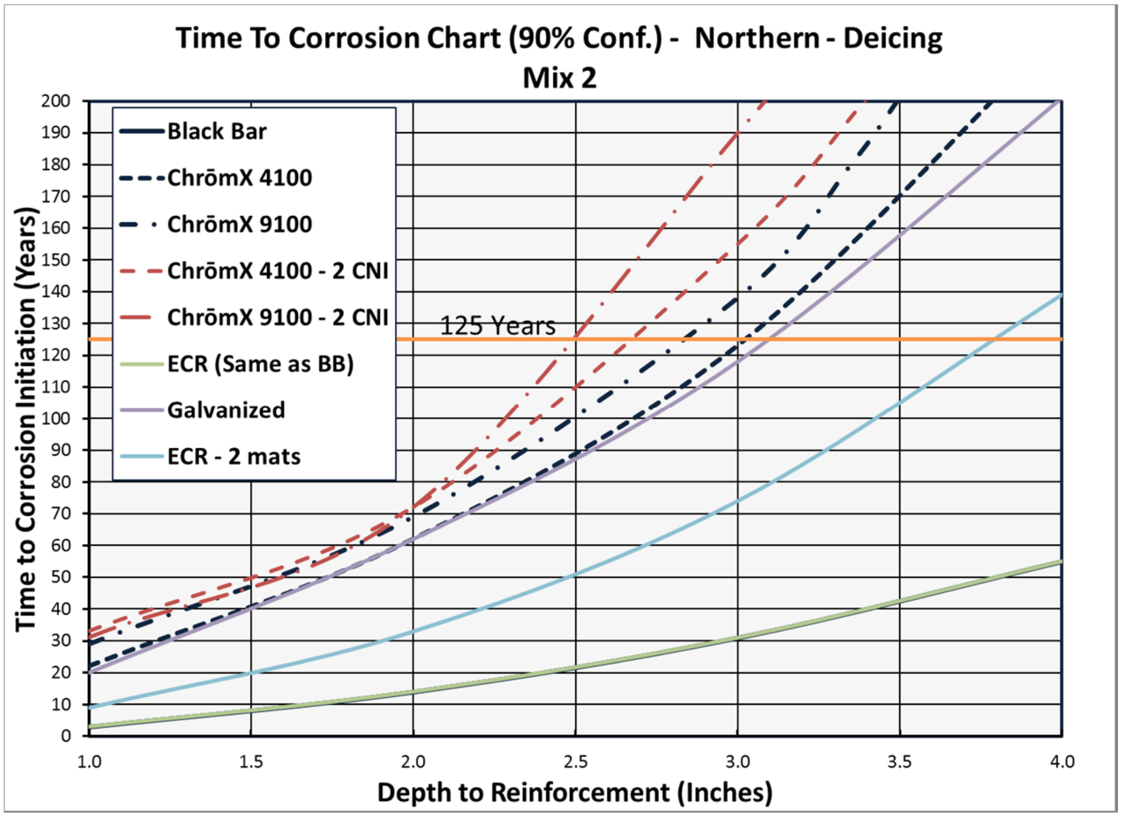
- STADIUM® Model Used
- Probabilistic Approach
- Moderately Severe Northern Environments in US.
- Demonstrates Performance Enhancements with A1035

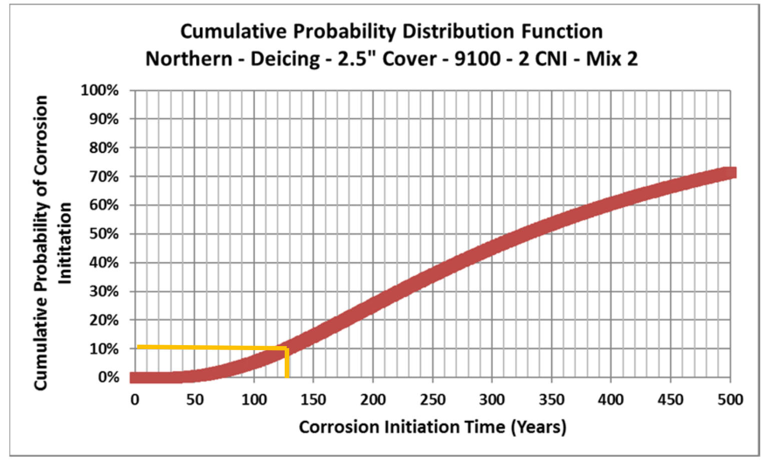
Property	**Mix 2**
Water/Binder Ratio	0.37
Total Cementitious	660
Type I (pcy)	469
Fly Ash F 25% (pcy)	165
Silica Fume 4% (pcy)	26
Fine Aggregates (pcy)	1300
Coarse Aggregates (pcy)	1700
Air	6.0

Probabilistic Analyses Inputs – Summary, Northern Deicing

No.	Service Life Variable		Units	Base Value	Std. Dev.	CoV
1	Exposure	NaCl Concentration	Mmol/L	588	176	0.3
2	Exposure	Exposure Duration	Days	50	-	-
3	Concrete Property	Porosity (Permeable Voids)	Fraction	0.125	-	-
4	Concrete Property	Ult. Ion Diffusion Coefficient (IDC)	e^{-11} m^2/s	2	0.5	0.25
5	Concrete Property	Moisture Transport Coefficient (MTC)	e^{-22} m^2	15	-	-
6	Geometry	Concrete Cover	in.	2.5	0.2	0.08

Probabilistic Analyses Results – Summary, Northern Deicing





Model Used	Time to corrosion (yrs) at different confidence levels		
	90%	80%	50%
BB	23	31	57
A1035 4% Cr	96	119	179
A1035 9% Cr	105	140	243
A1035 4% Cr +2gpy CNI	111	153	282
A1035 9% Cr +2gpy CNI	126	175	327
ECR	23	31	57
ECR – 2 mats	55	66	97
HDG	93	114	166

Note: - Mix 2 (Good Performance)
- 2.5” Cover

Case Study for Wall/Deck Exposed to Airborne Chloride

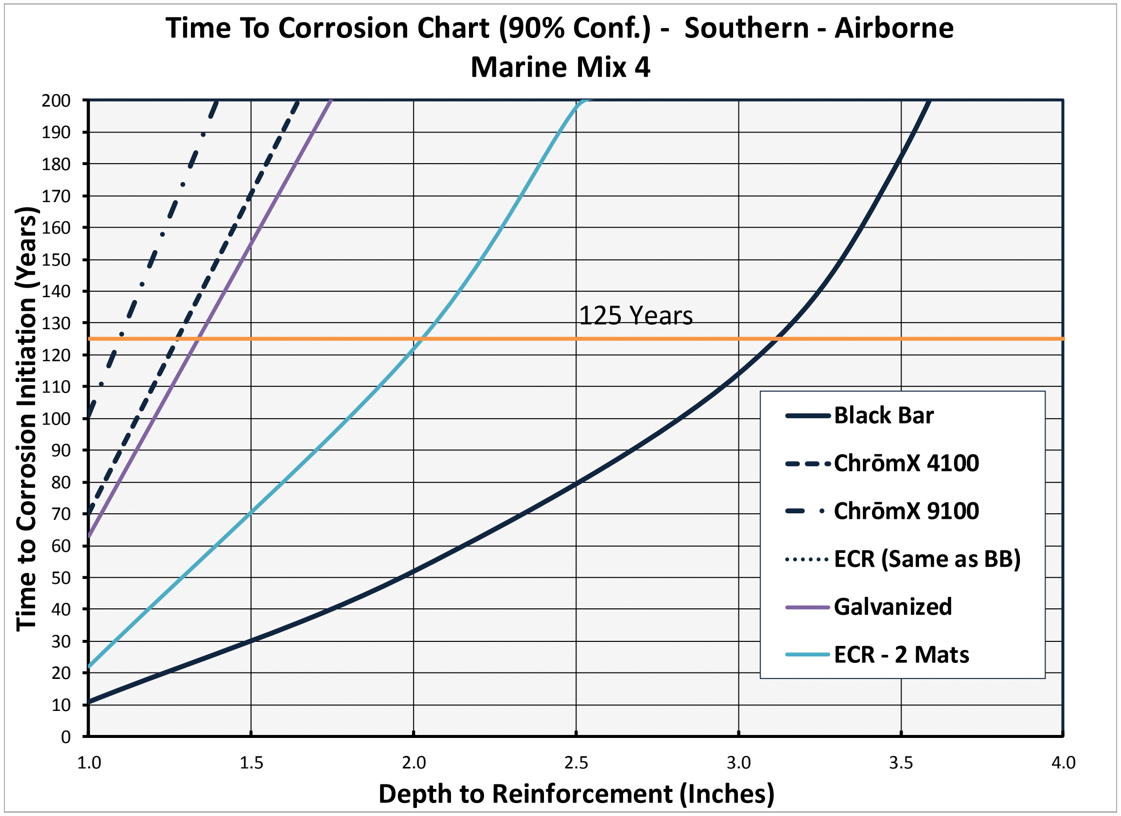
- STADIUM® Model Used
- Probabilistic Approach
- Southern Marine Environment in US.
- Demonstrates Performance Enhancements with A1035

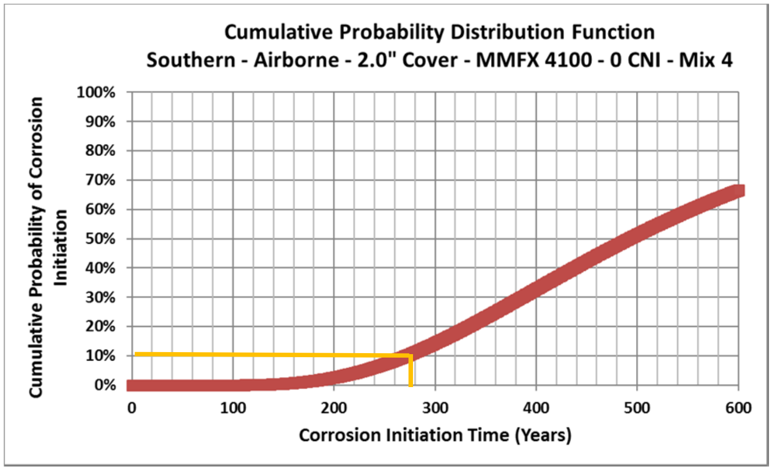
Property	Mix 4
Water/Binder Ratio	0.45
Total Cementitious (pcy)	600
Cement Type I (pcy)	480
Fly Ash 20% (pcy)	120
Fine Aggregates (pcy)	1385
Coarse Aggregates (pcy)	1600
Air	6%

Probabilistic Analyses Inputs – Summary, Southern Airborne

No.	Service Life Variable		Units	Base Value	Std. Dev.	CoV
1	Exposure	Salinity of Seawater	‰	35	10.5	0.3
2	Exposure	Airborne Factor	Fraction	0.3	-	-
3	Concrete Property	Porosity (Permeable Voids)	Fraction	0.125	0.01	0.08
4	Concrete Property	Ult. Ion Diffusion Coefficient (IDC)	e^{-11} m^2/s	3	0.75	0.25
5	Concrete Property	Moisture Transport Coefficient (MTC)	e^{-22} m^2	40	-	-
6	Geometry	Concrete Cover	in.	2.0	0.16	0.08

Probabilistic Analyses Results – Summary, Southern Airborne





Reinforcement Type	Time to corrosion (yrs) at different confidence levels		
	90%	80%	50%
BB	52	67	113
A1035 4% Cr	>200	>200	>200
A1035 9% Cr	>200	>200	>200
ECR	52	67	113
HDG	>200	>200	>200
ECR – 2 Mats	122	150	224

Note: - Mix 4 (Moderate Performance)
- 2.0” Cover

Conclusions

- A1035 low Cr alloys increase the chloride threshold value for corrosion initiation
- Additions of CNI to concrete with A1035 low Cr reinforcing bars enhances performance
- Modeling of performance shows a significant increase in service life with A1035 low Cr alloys with and without CNI

For More Information

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