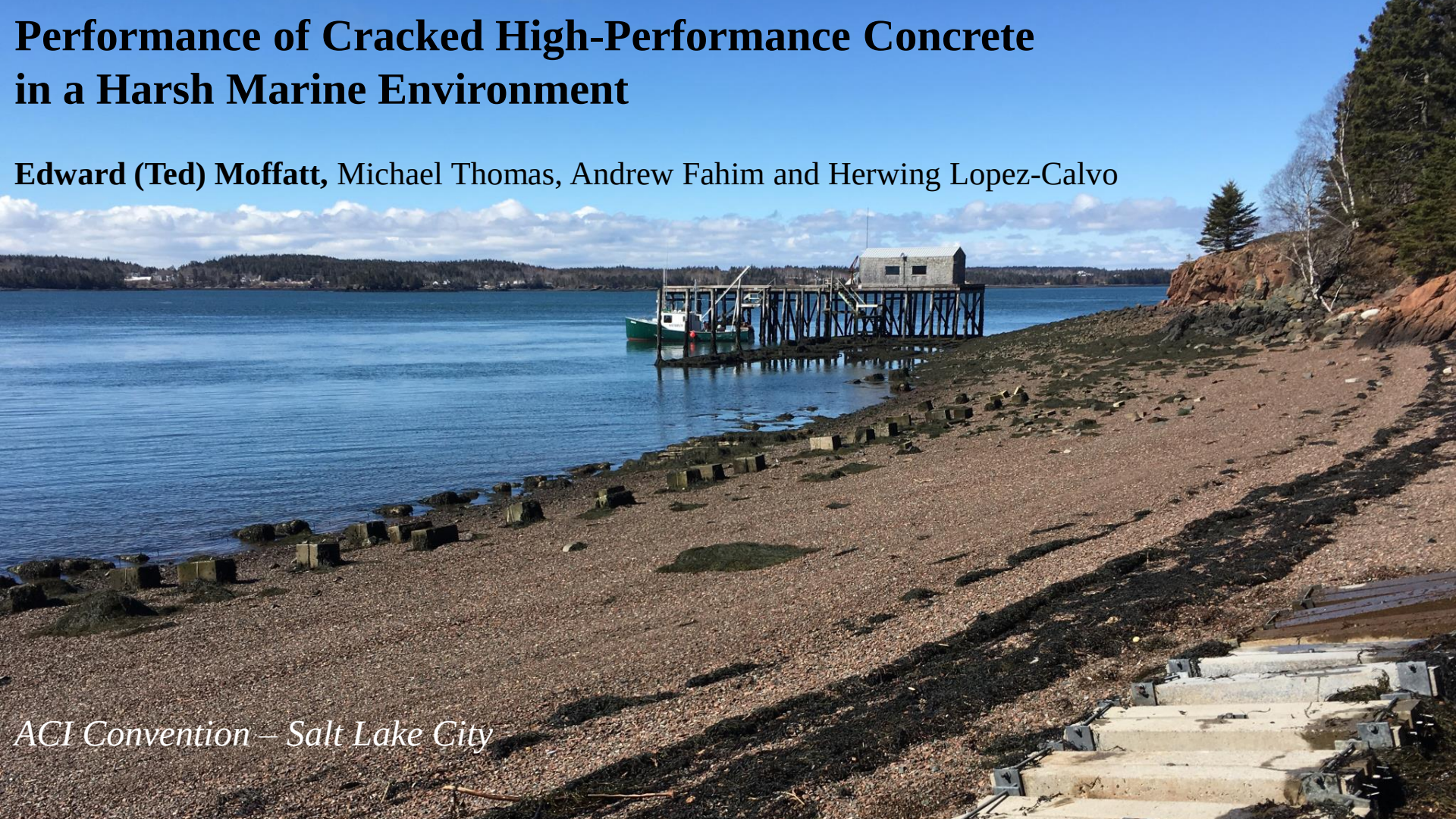
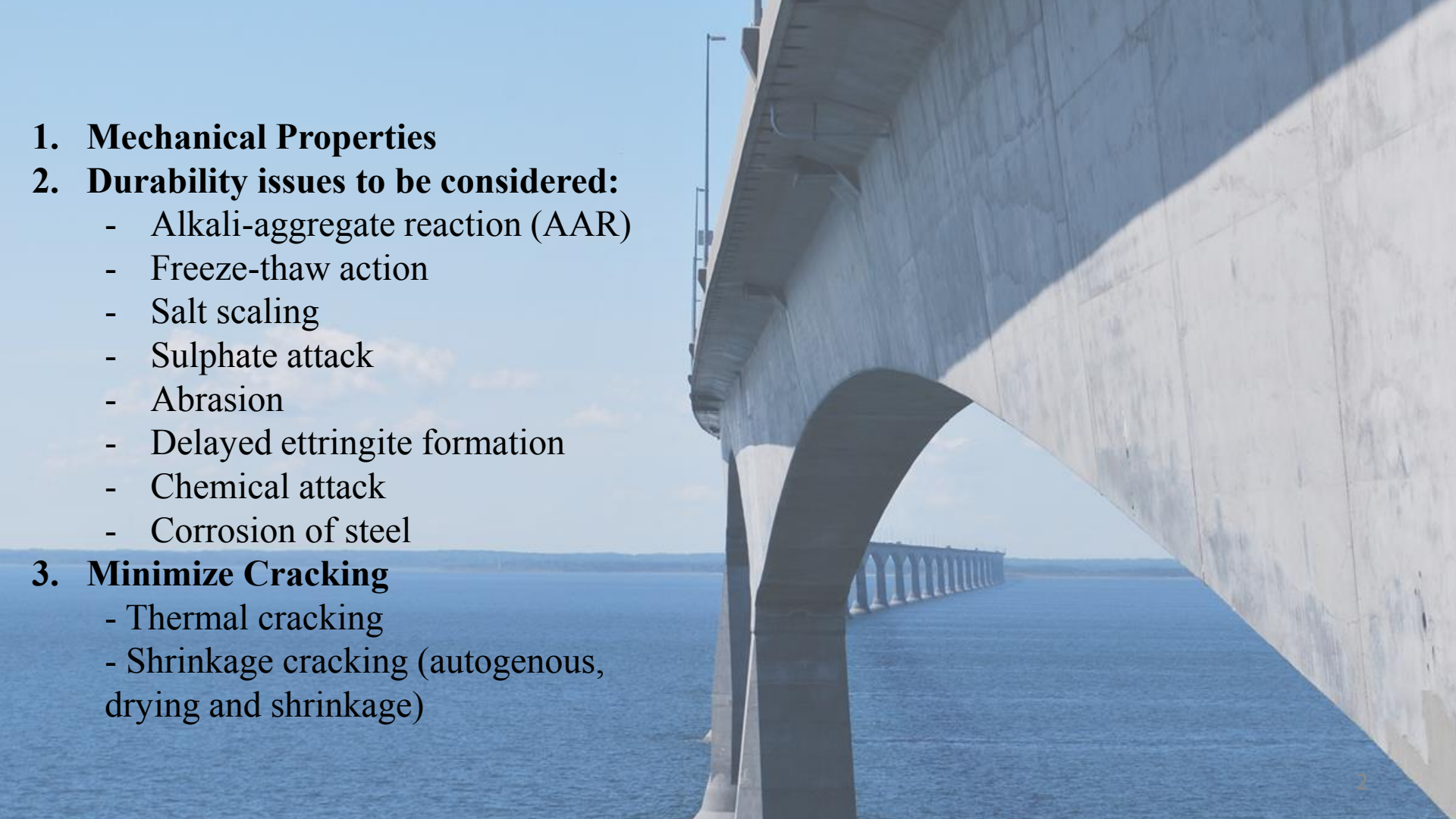
Performance of Cracked High-Performance Concrete in a Harsh Marine Environment

Edward (Ted) Moffatt, Michael Thomas, Andrew Fahim and Herwing Lopez-Calvo

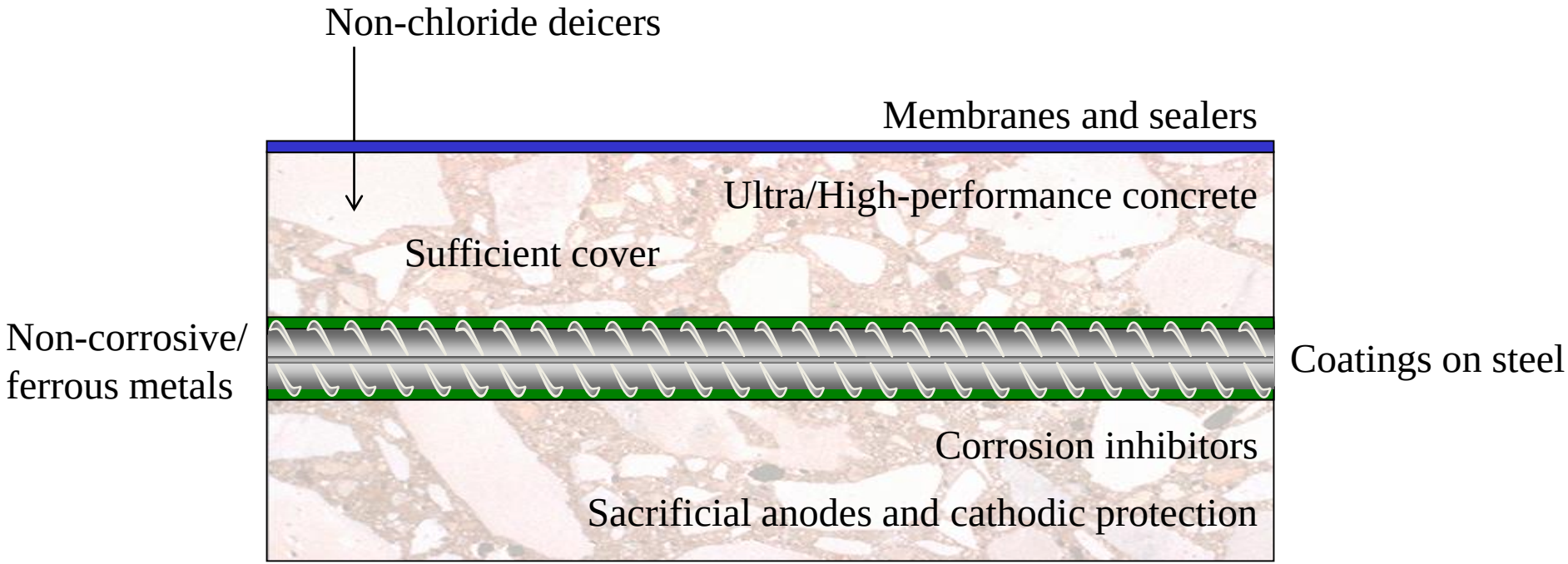


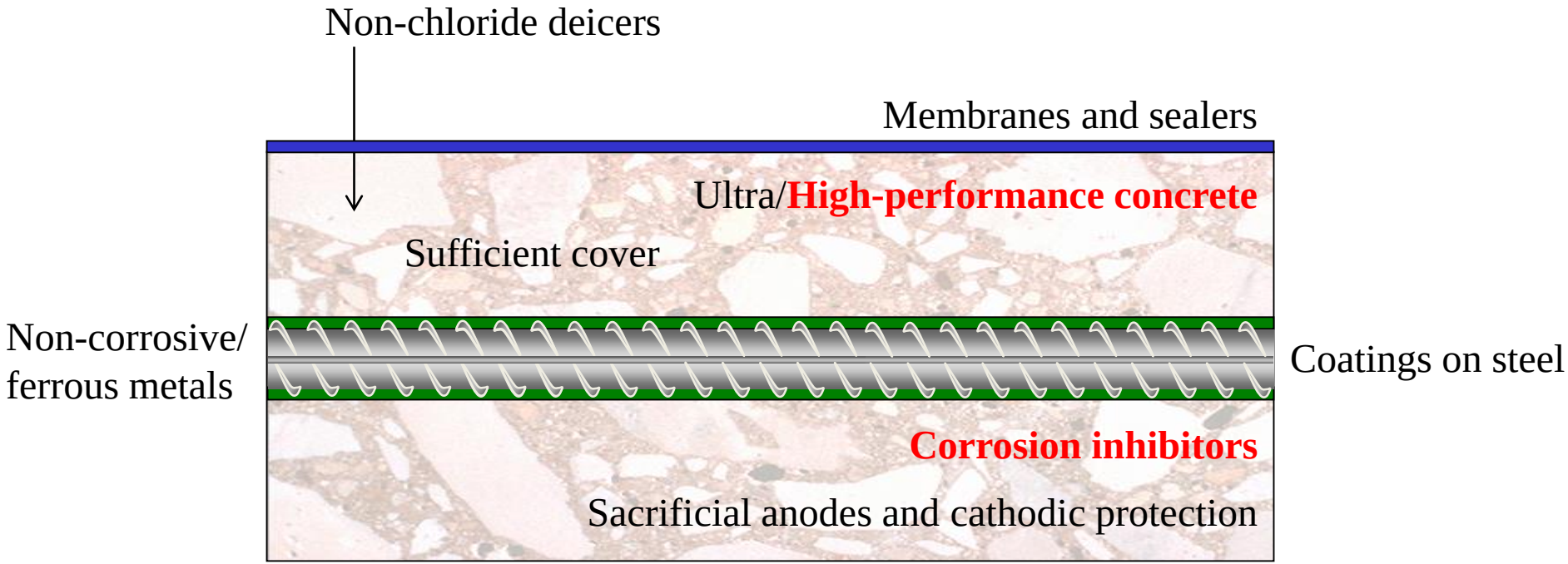
ACI Convention – Salt Lake City



1. **Mechanical Properties**
2. **Durability issues to be considered:**
   - Alkali-aggregate reaction (AAR)
   - Freeze-thaw action
   - Salt scaling
   - Sulphate attack
   - Abrasion
   - Delayed ettringite formation
   - Chemical attack
   - Corrosion of steel
3. **Minimize Cracking**
   - Thermal cracking
   - Shrinkage cracking (autogenous, drying and shrinkage)


Seawater
Road salts


Non-chloride deicers
Membranes and sealers
Ultra/High-performance concrete
Sufficient cover
Non-corrosive/
ferrous metals
Coatings on steel
Corrosion inhibitors
Sacrificial anodes and cathodic protection


Non-chloride deicers
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Sufficient cover
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Coatings on steel
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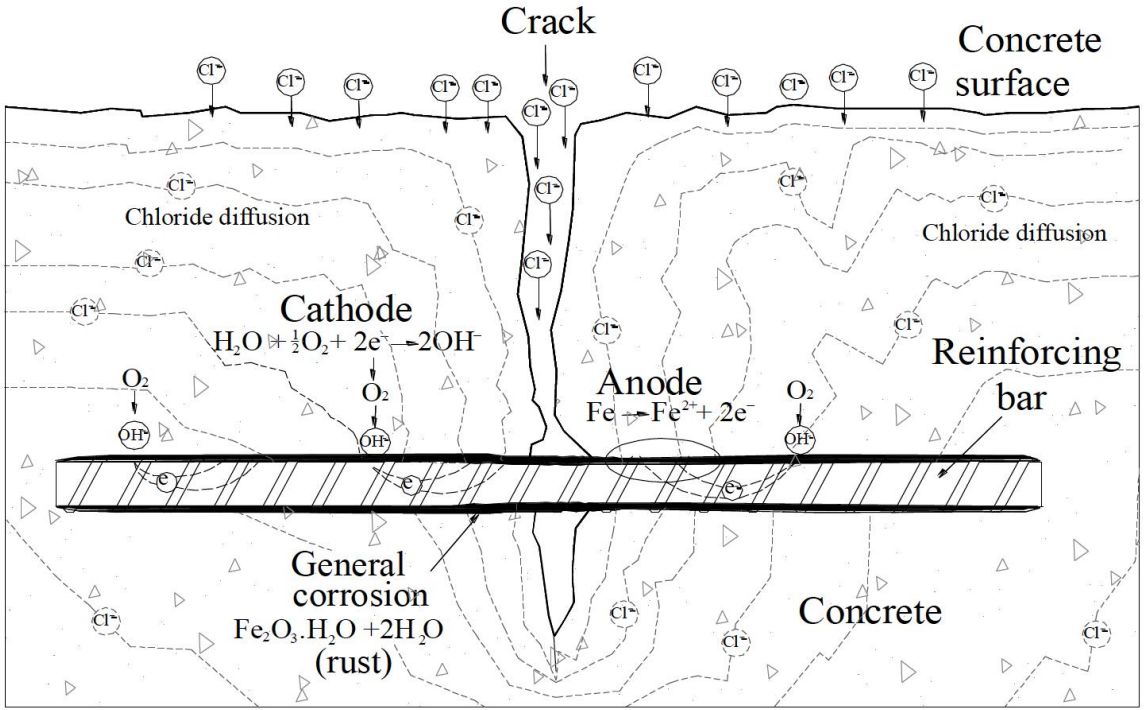
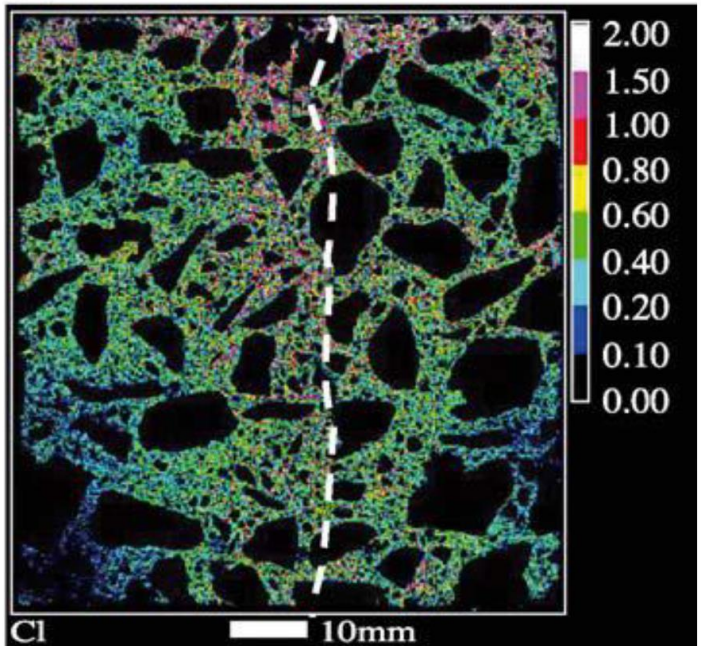
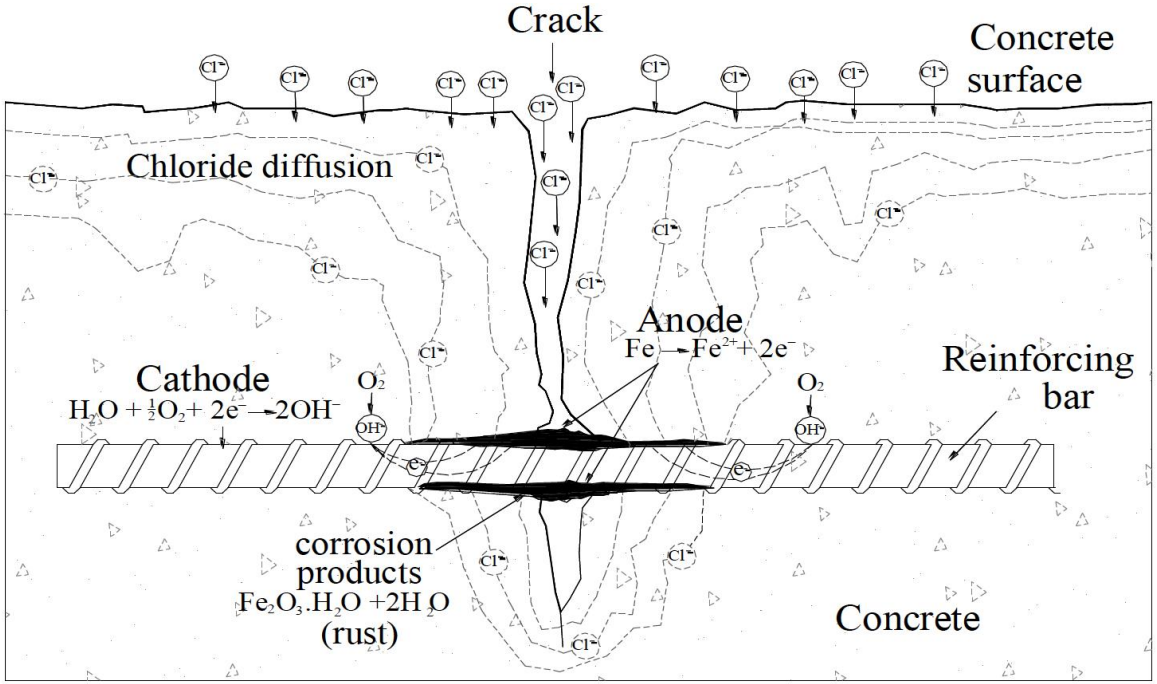
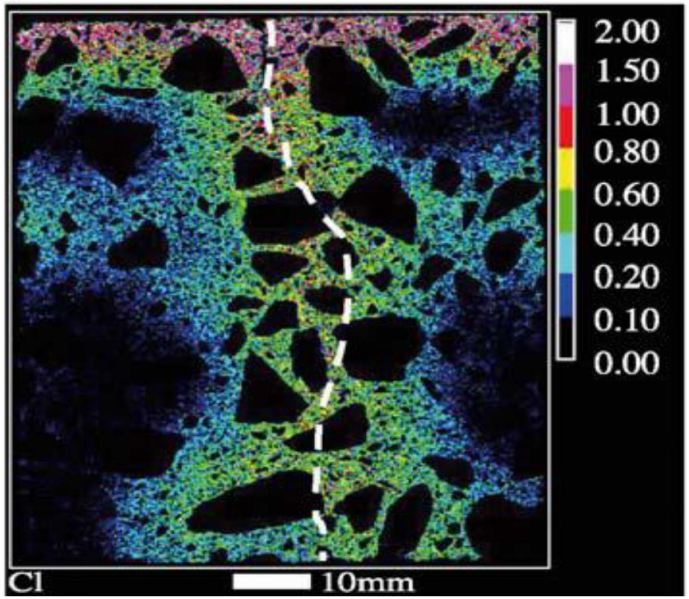
Sacrificial anodes and cathodic protection


Crack
Concrete surface
Chloride diffusion
Chloride diffusion
Cathode
$H_2O + \frac{1}{2}O_2 + 2e^- \rightarrow 2OH^-$
Anode
$Fe \rightarrow Fe^{2+} + 2e^-$
Reinforcing bar
General corrosion
$Fe_2O_3.H_2O + 2H_2O$
(rust)
Concrete

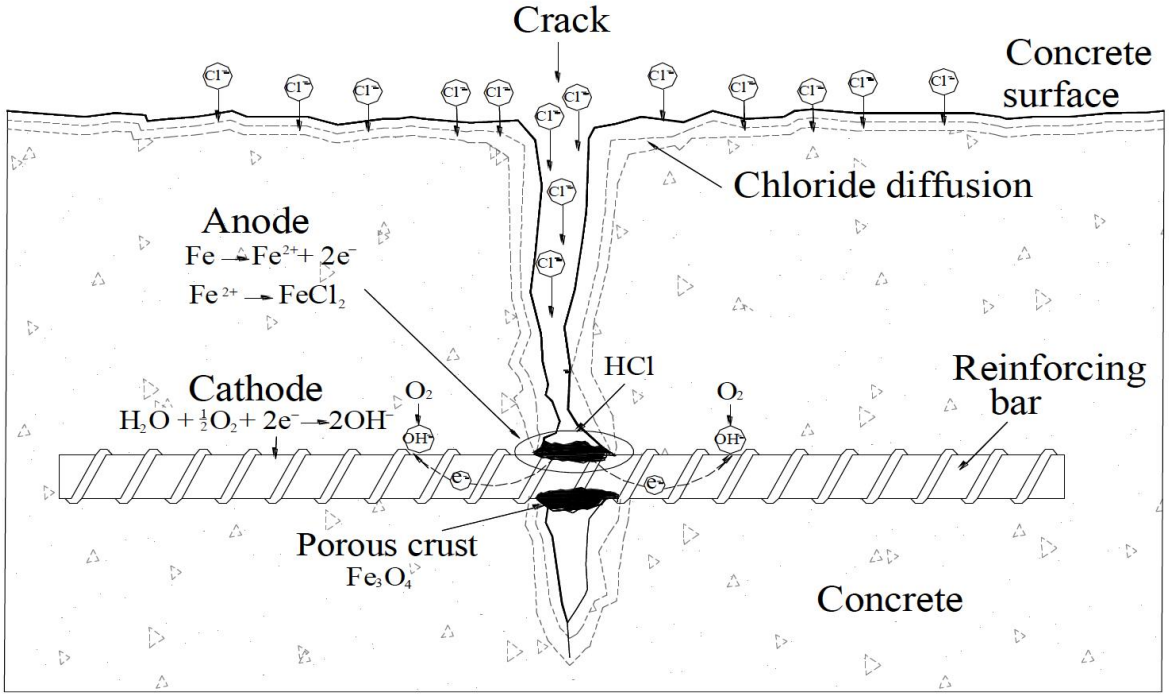

2.00
1.50
1.00
0.80
0.60
0.40
0.20
0.10
0.00
Cl
10mm

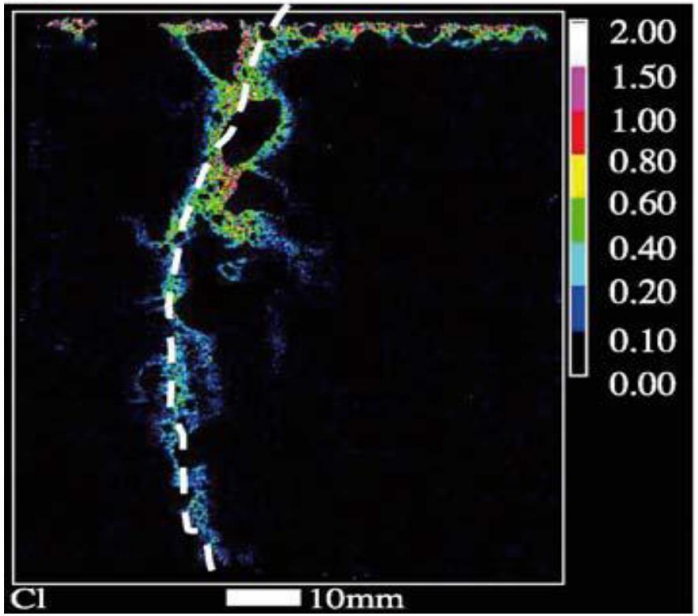
(Win, 2004)


Crack
Concrete surface
Chloride diffusion
Anode
$Fe \rightarrow Fe^{2+} + 2e^-$
Cathode
$H_2O + \frac{1}{2}O_2 + 2e^- \rightarrow 2OH^-$
O_2
OH^-
e^-
Reinforcing bar
corrosion products
$Fe_2O_3.H_2O + 2H_2O$
(rust)
Concrete
Cl^-


2.00
1.50
1.00
0.80
0.60
0.40
0.20
0.10
0.00
Cl
10mm

(Win, 2004)


Crack
Concrete surface
Chloride diffusion
Anode
Fe → Fe2+ + 2e−
Fe2+ → FeCl2
Cathode
H2O + ½O2 + 2e− → 2OH−
HCl
O2
OH−
e−
Reinforcing bar
Porous crust
Fe3O4
Concrete


2.00
1.50
1.00
0.80
0.60
0.40
0.20
0.10
0.00
Cl
10mm

(Win, 2004)

High Performance Concrete – concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.

ACI Concrete Terminology

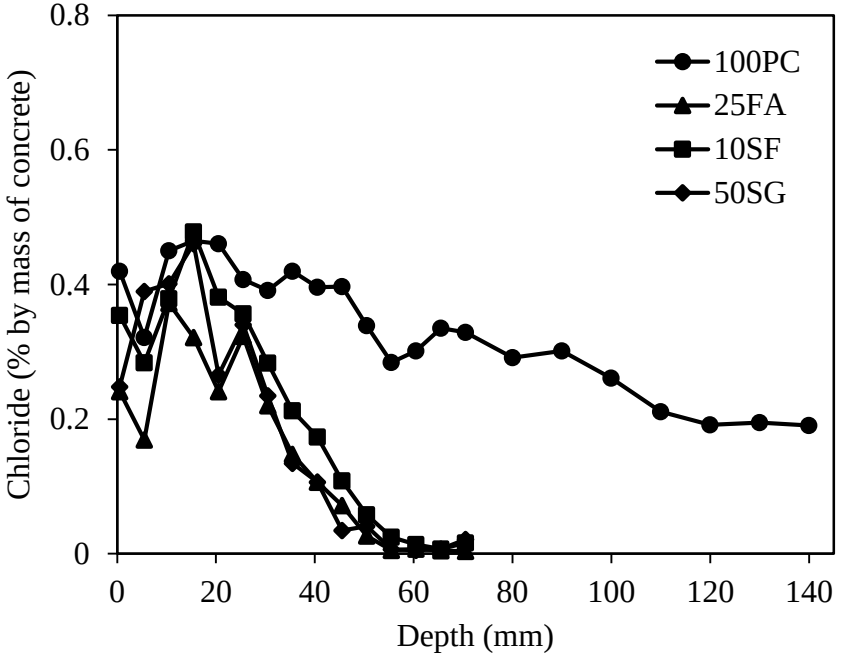
Supplementary Cementing Materials (SCMs):

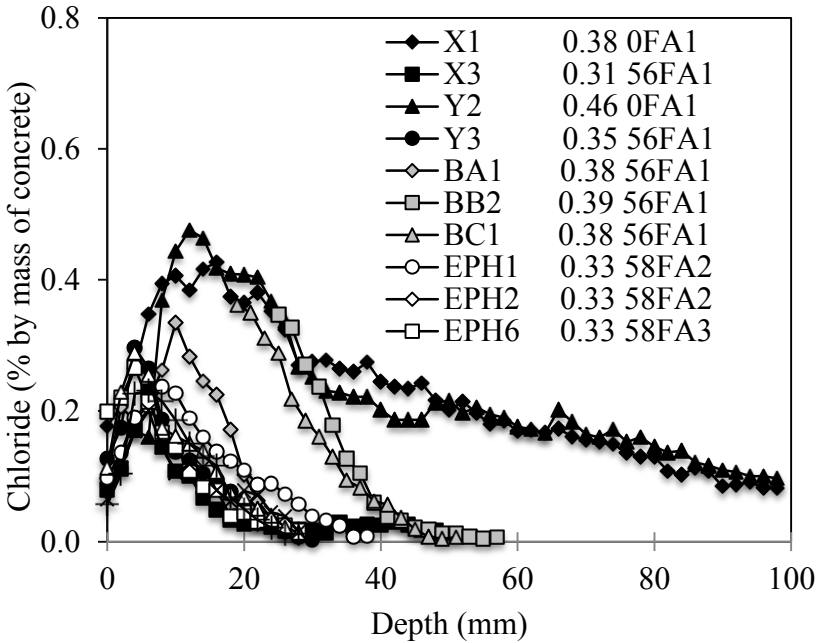
- Fly Ash
- Silica Fume

Corrosion Inhibitors:

- Calcium Nitrite inhibitor (CNI)
- Disodium Tetrapropenyl succinate (DTS)

Performance of SCM Concrete – Treat Island (25 to 27 Years)



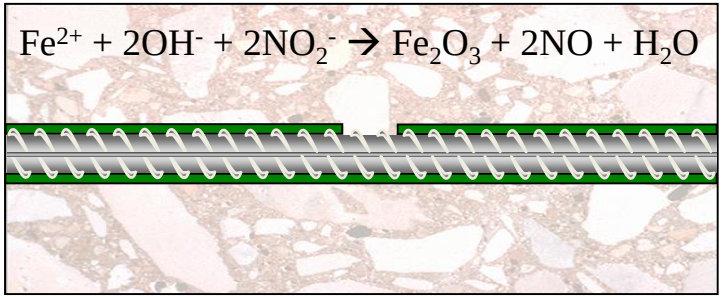


Fahim, A. Moffatt, E.G. and Thomas, M.D.A. (2017). Corrosion Resistance of Concrete Incorporating Supplementary Cementing Materials in a Marine Environment. International Concrete, SP-320-18, pp. 18.1-18.14.

Moffatt, E.G., Thomas, M.D.A., and Fahim, A. (2017). Performance of High-Volume Fly Ash Concrete in Marine Environment. Cement and Concrete Research. 102, pp. 127-135.

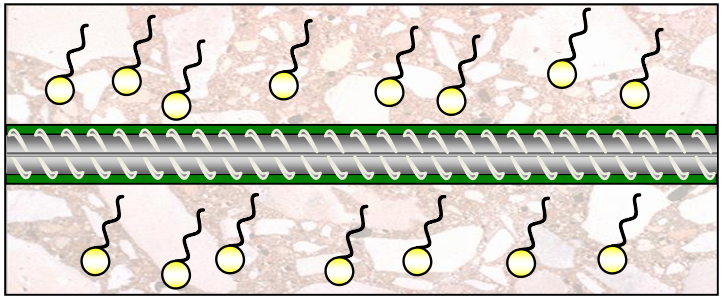
Calcium Nitrite Inhibitor (CNI)

- inorganic corrosion inhibitor
- helps stabilize the passive layer on the steel
- competes with chloride ions for ferrous ions
- acts as an accelerator



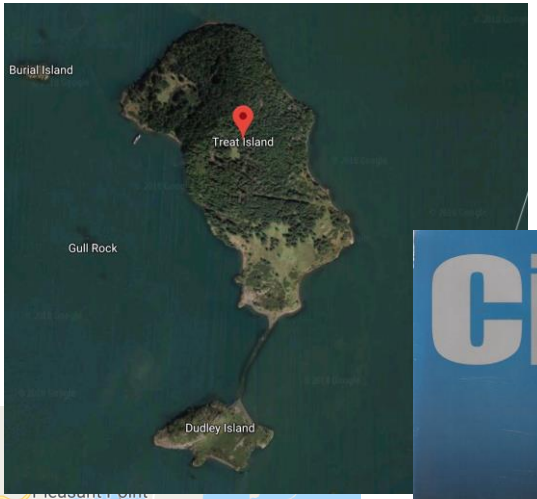
Disodium Tetrapropenyl Succinate (DTS)

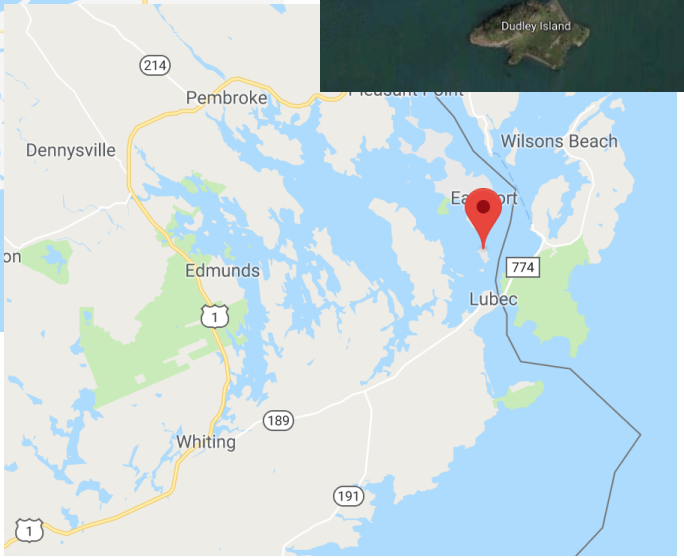
- organic corrosion inhibitor
- salt of alkenyl-substituted succinic acid (ASSA)
- contains an air-entraining admixture

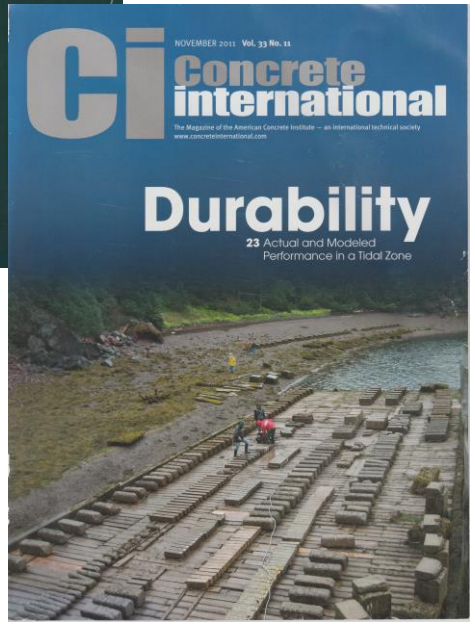



Treat Island, Maine, U.S.A.


NEW
BRUNSWICK
Fredericton
Moncton
PRINCE
EDWARD
ISLAND
New Glasgow
Saint John
MAINE


Burial Island
Treat Island
Gull Rock
Dudley Island


214
Pembroke
Dennysville
Wilsons Beach
Edmunds
774
Lubec
1
189
Whiting
191
1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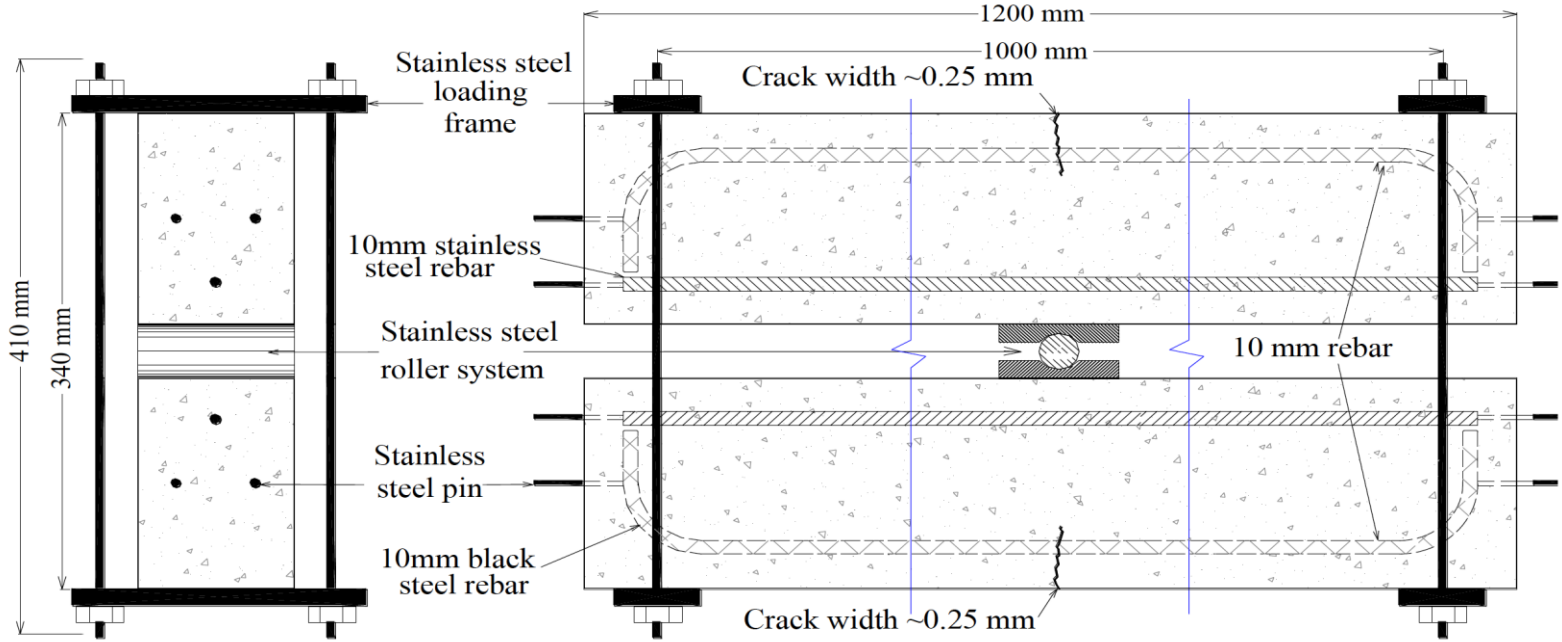
www.concreteinternational.com
Durability
23 Actual and Modeled
Performance in a Tidal Zone


Treat Island, Maine, U.S.A.

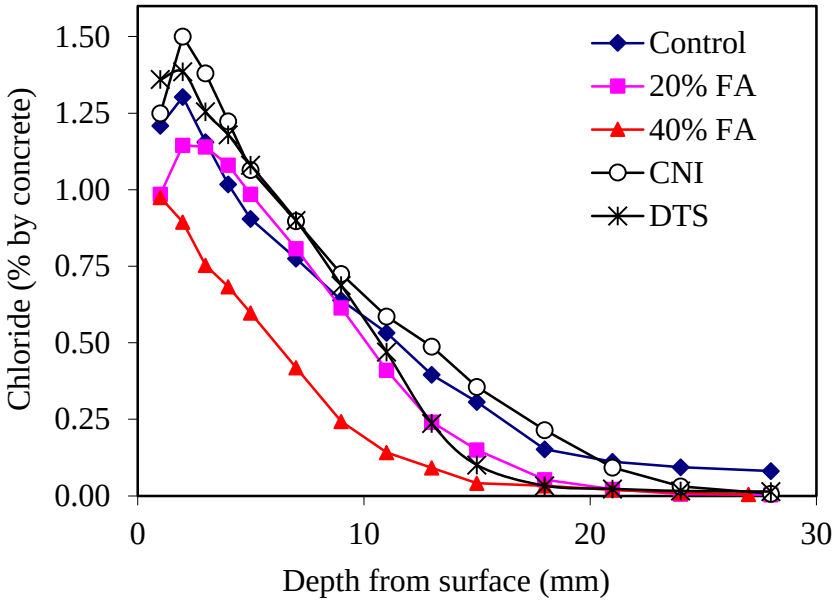
1

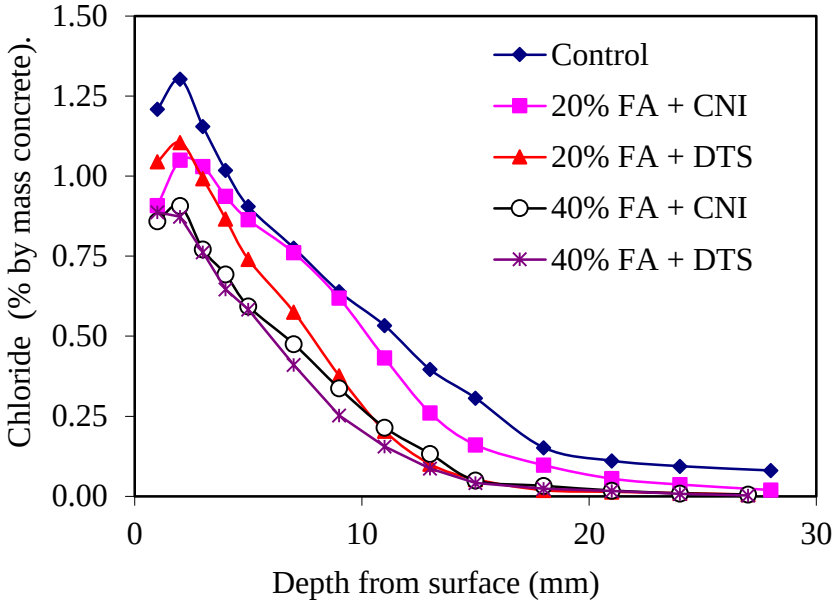
Portland Cement: ASTM Type I with 8% silica fume replacement
Fly Ash: ASTM Type F (CaO = 2.96%)
W/CM = 0.37
Cementitious content = 470 kg/m^3 (790 lb/yd^3)
Air = 6-8%
Slump = 140-180 mm (5.5-7.0 in.)

	Mix	Mixture Properties
Double combinations	1	100% PC
	2	20% FA
	3	40% FA
	4	12.5 L/m^3 CNI
	5	5 L/m^3 DTS
Triple combinations	6	20% FA + 12.5 L/m^3 CNI
	7	20% FA + 5 L/m^3 DTS
	8	40% FA + 12.5 L/m^3 CNI
	9	40% FA + 5 L/m^3 DTS

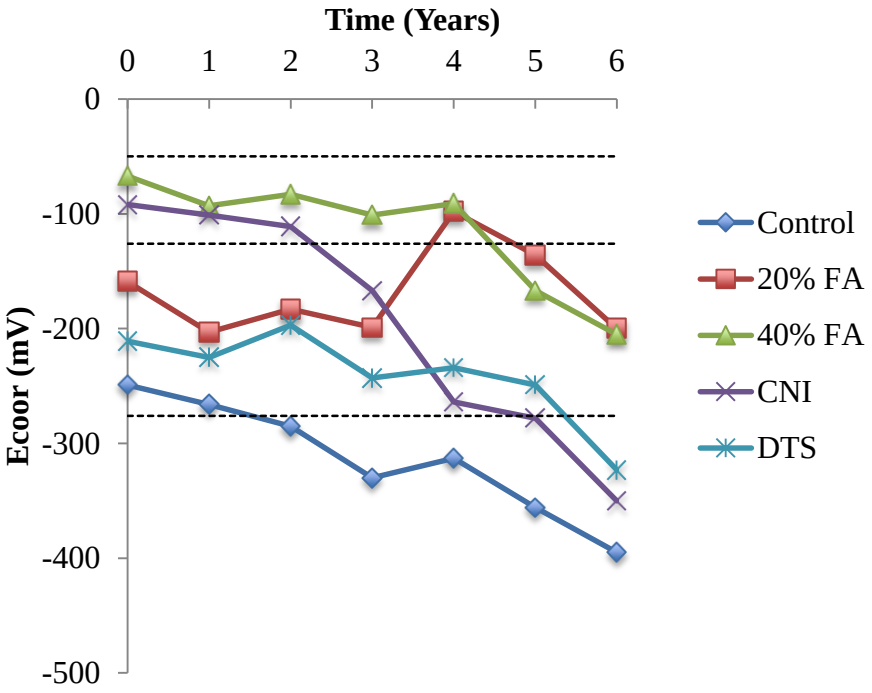

1200 mm
1000 mm
Crack width ~0.25 mm
Stainless steel loading frame
10mm stainless steel rebar
Stainless steel roller system
Stainless steel pin
10mm black steel rebar
10 mm rebar
Crack width ~0.25 mm
410 mm
340 mm

Mix	Mixture Properties	Compressive Strength (MPa)	Diff. Coefficient ($x10^{-12}$ m^2/s)
1	100% PC	49.8	1.90
2	20% FA	56.8	1.40
3	40% FA	50.4	0.85
4	12.5 L/m^3 CNI	62.2	1.80
5	5 L/m^3 DTS	45.9	1.30
6	20% FA + 12.5 L/m^3 CNI	47.2	1.40
7	20% FA + 5 L/m^3 DTS	39.3	0.83
8	40% FA + 12.5 L/m^3 CNI	45.1	0.85
9	40% FA + 5 L/m^3 DTS	36.4	0.77

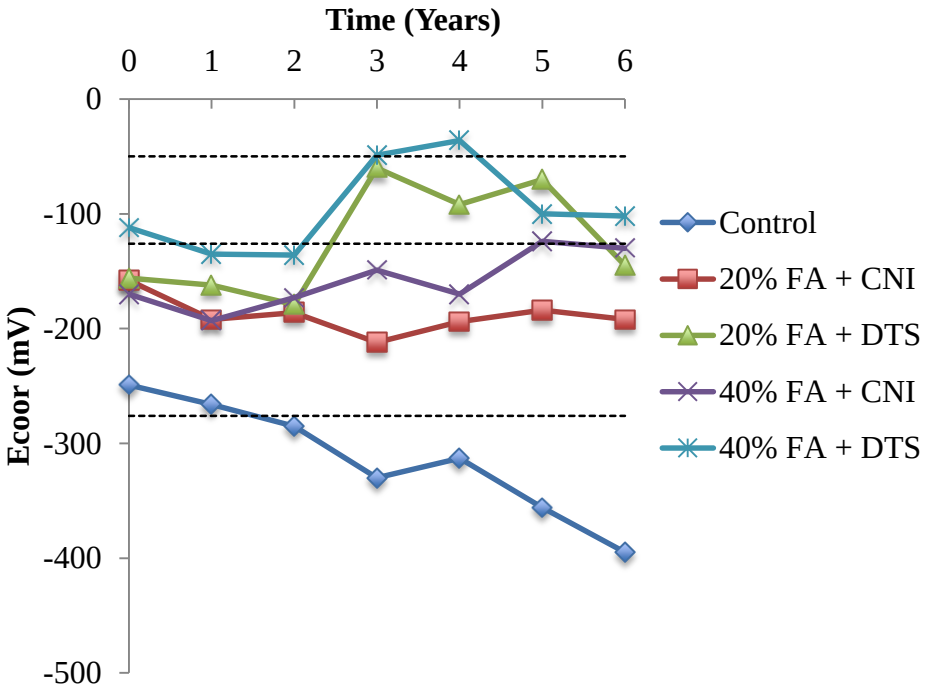

Chloride (% by concrete)
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
10
20
30
Depth from surface (mm)
Control
20% FA
40% FA
CNI
DTS


Chloride (% by mass concrete).
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
10
20
30
Depth from surface (mm)
Control
20% FA + CNI
20% FA + DTS
40% FA + CNI
40% FA + DTS

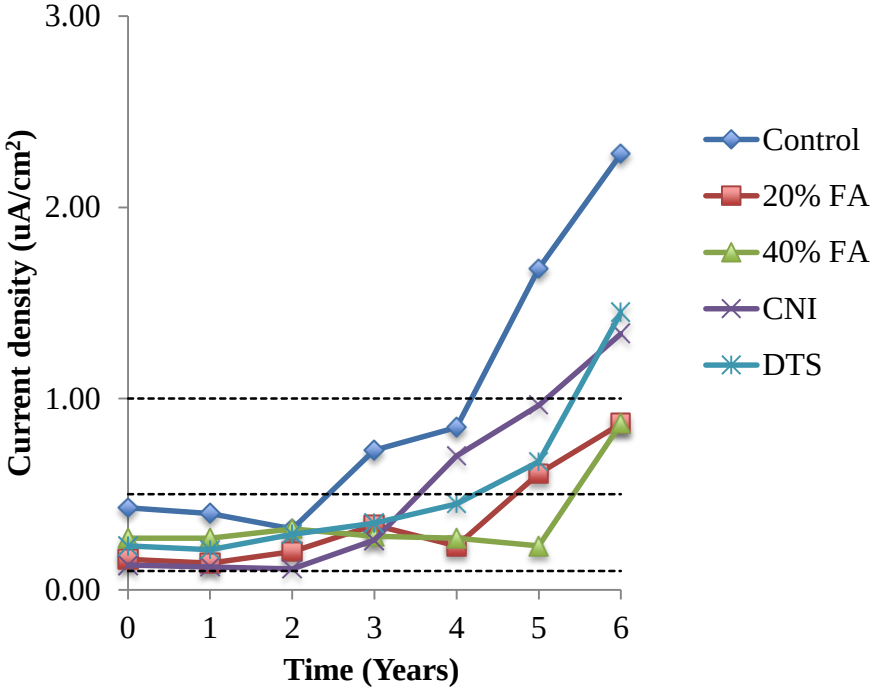
Double combinations



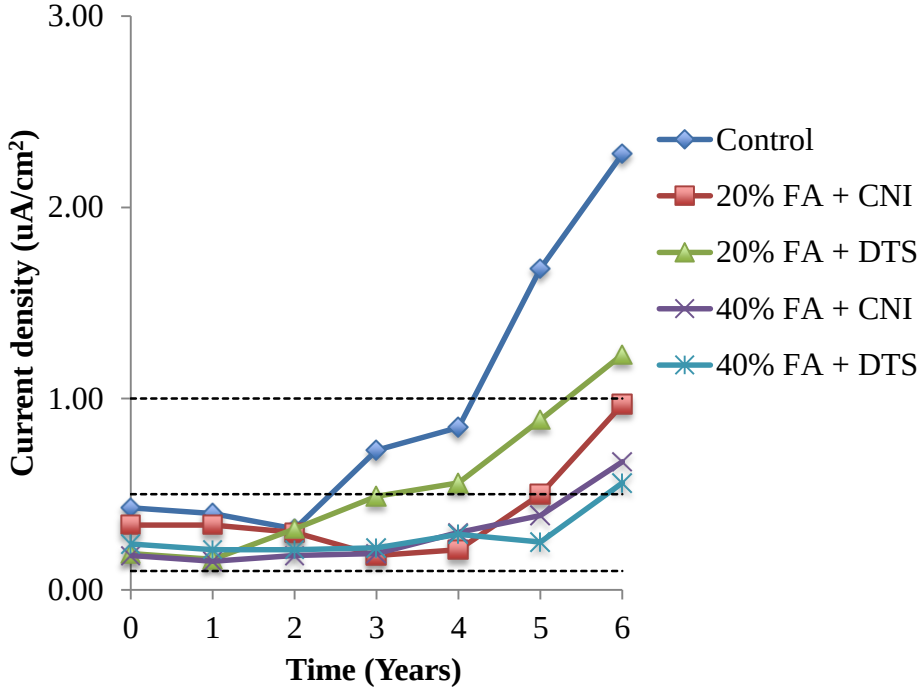
Triple combinations



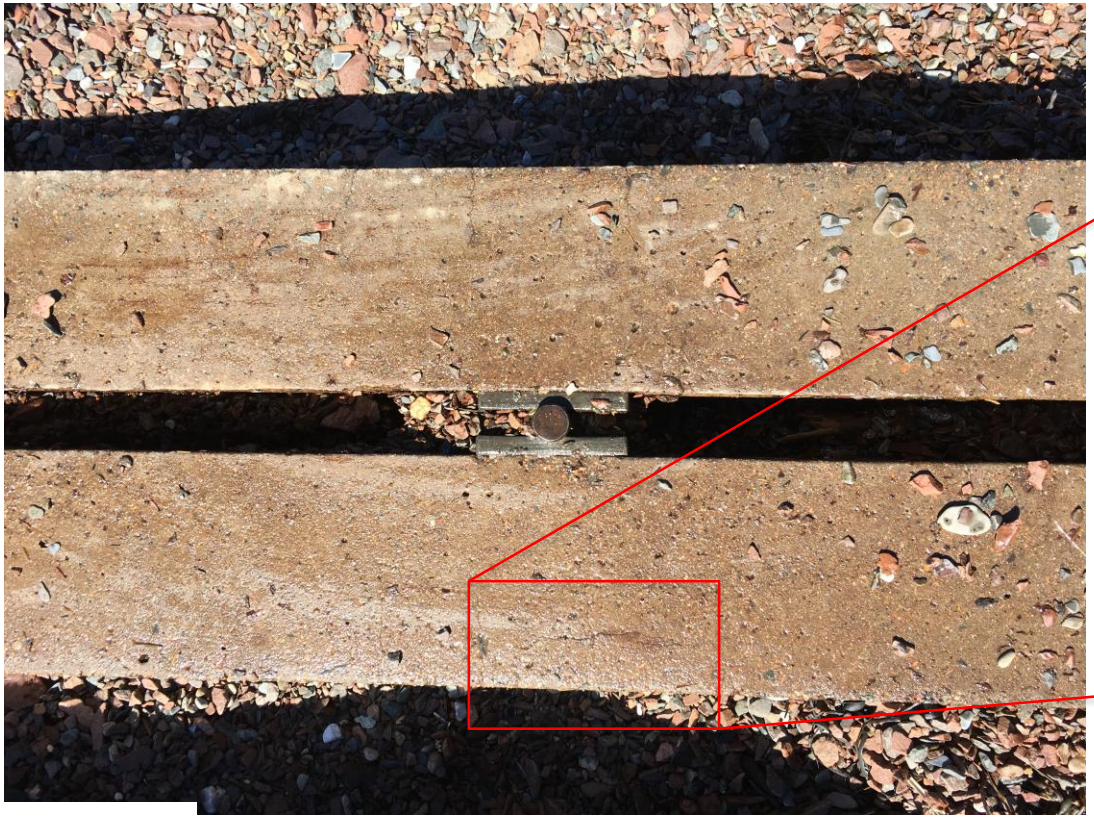
Double combinations

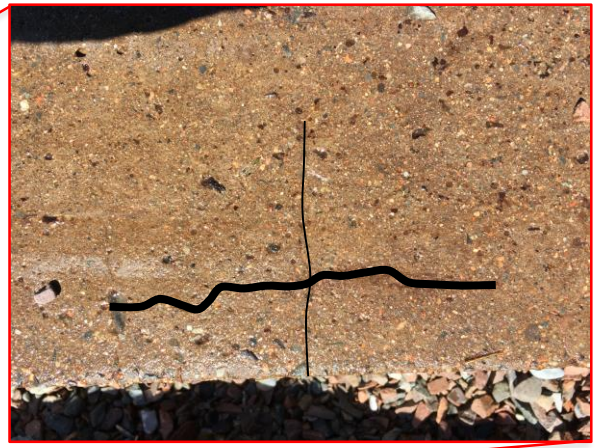


Triple combinations



100% PC





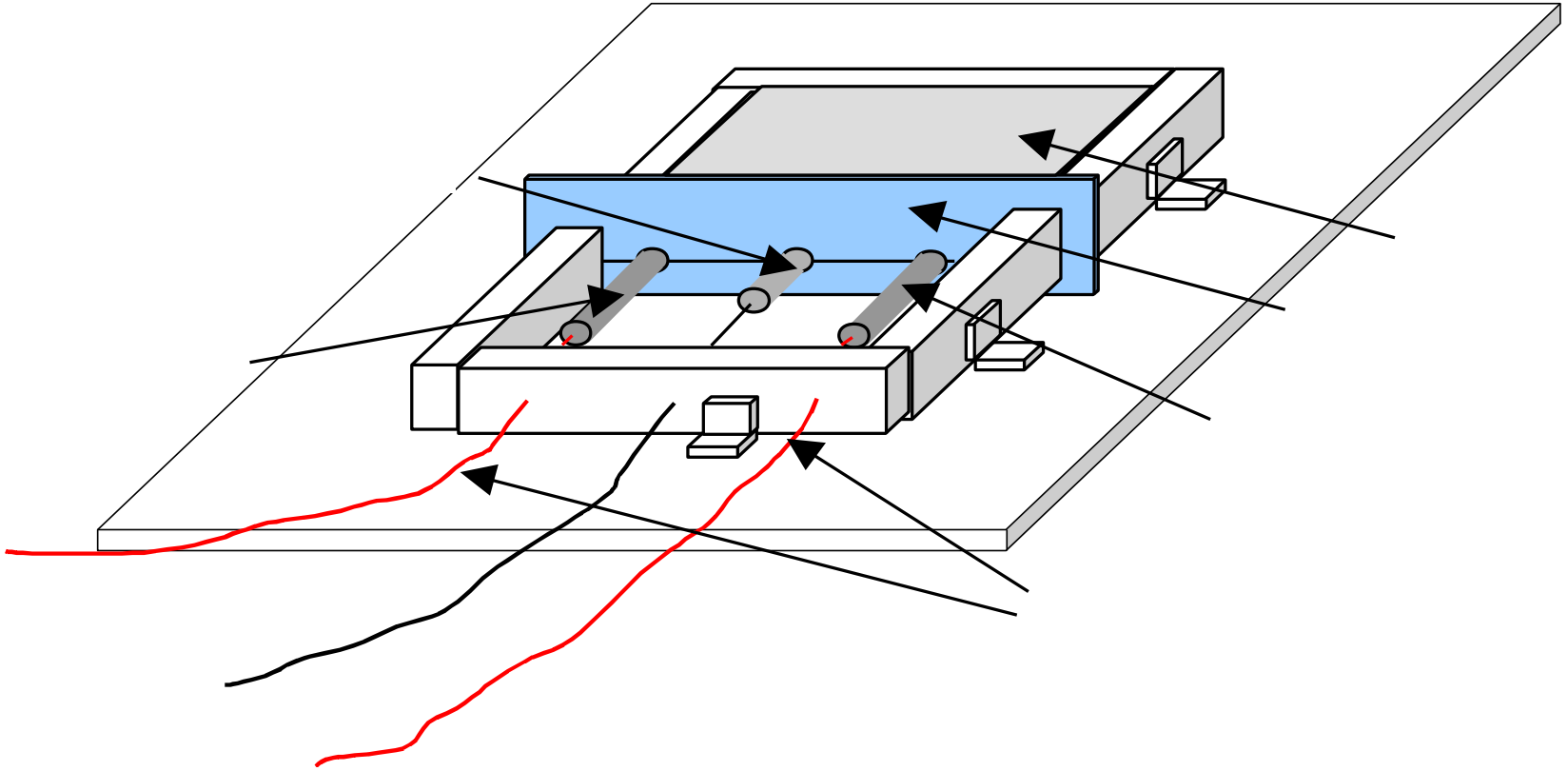
DTS


Treat Island, Maine, U.S.A.

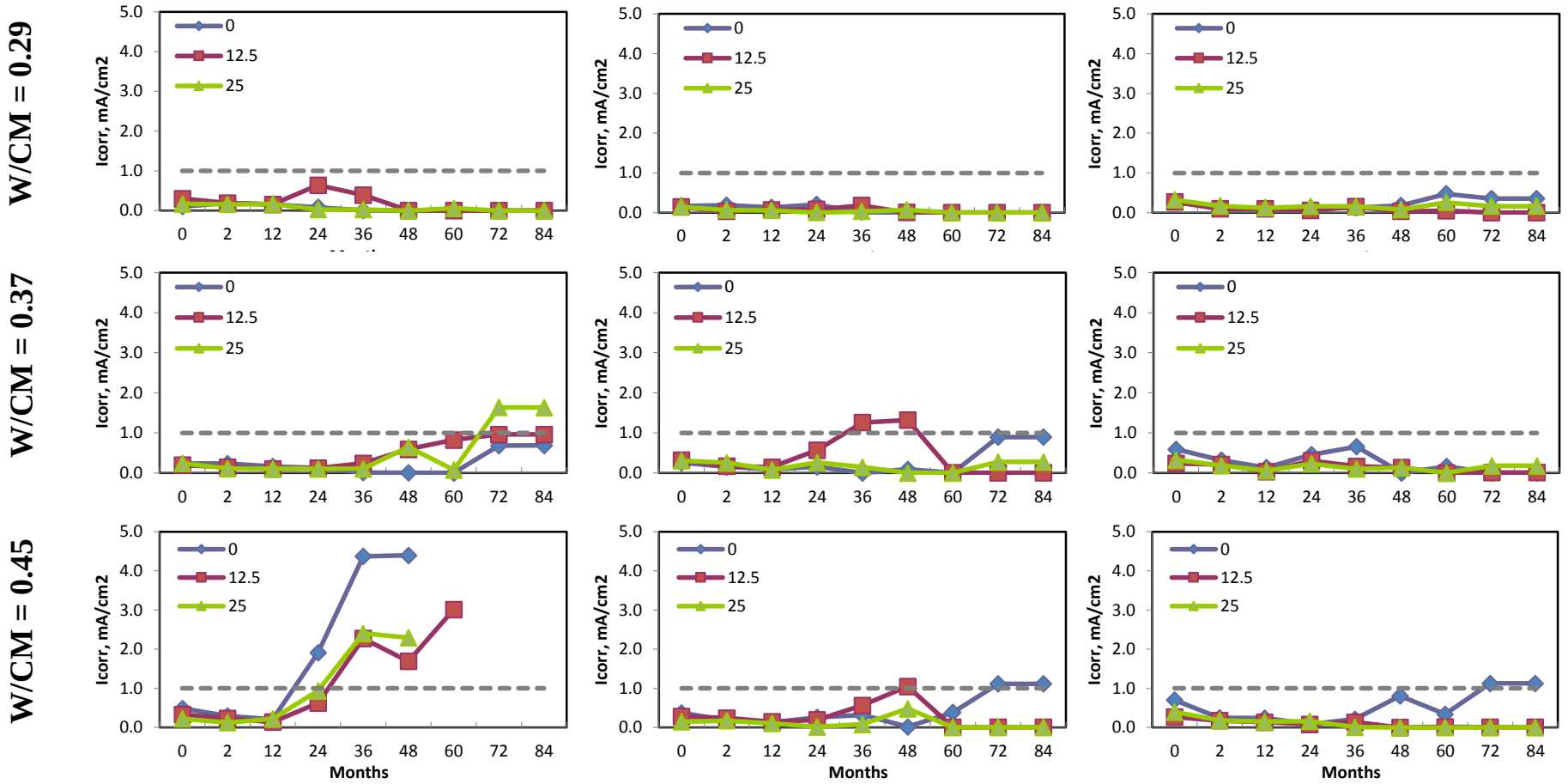
2

Variables	No. of Levels	Description
W/CM	3	0.29, 0.37, 0.45
Fly Ash	3	0, 20, 40 %
CNI	3	0, 12.5, 25 L/m^3
Crack	3	0, 0.25, 0.50 mm

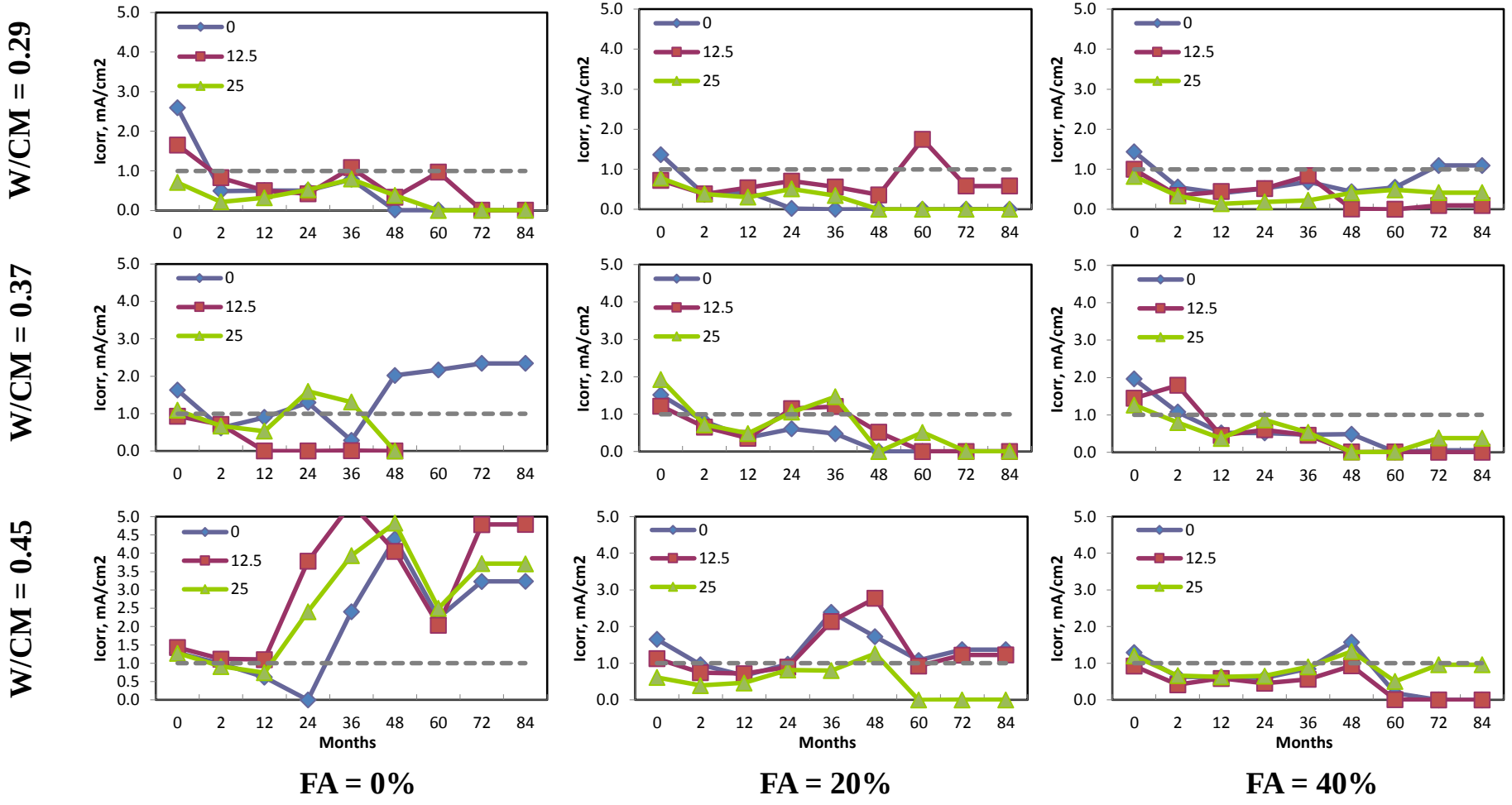
Portland Cement: ASTM Type I with 8% silica fume replacement
Fly Ash: ASTM Type F (CaO = 2.96%)
Cementitious content = 360-540 kg/m^3
Air = 6-8%
Slump = 140-180 mm (5.5-7.0 in.)



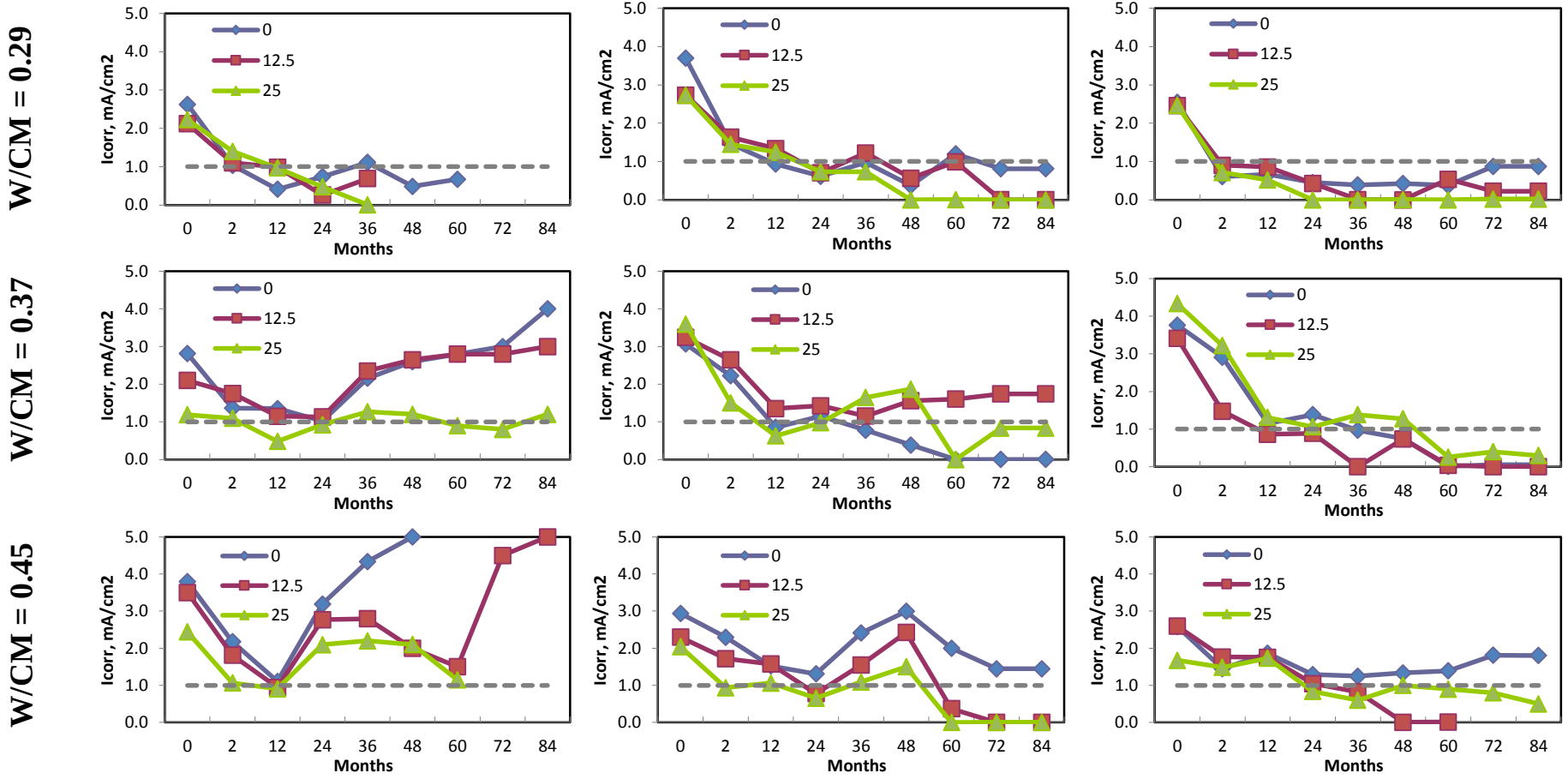
Crack Width (0 mm)



Crack Width (0.25 mm)



Crack Width (0.50 mm)



W/CM = 0.29, FA= 0%, CNI = 0 L/m^3

0mm 0.25mm 0.50mm

W/CM = 0.29, FA= 40%, CNI = 25 L/m^3

0mm 0.25mm 0.50mm

W/CM = 0.37, FA= 0%, CNI = 0 L/m^3

W/CM = 0.37, FA= 40%, CNI = 25 L/m^3

0mm 0.25mm 0.50mm

0mm 0.25mm 0.50mm

W/CM = 0.45, FA= 0%, CNI = 0 L/m^3

0mm 0.25mm 0.50mm

W/CM = 0.45, FA= 40%, CNI = 25 L/m^3

0mm 0.25mm 0.50mm

Conclusions

- **Compressive strength** of HPC is significantly influenced by the combination of CIAs and SCMs.
- The combination of CIA and SCMs showed a synergistic effect in reducing **permeability** of HPC.
- CNI or DTS alone is relatively ineffective in providing protection of reinforcing steel in precracked and cracked HPC. However, the presence of SCMs showed a reduced **corrosion rate**.
- **W/CM** has a marked influence on cracking and corrosion.
- Based on the studied variables, the **width of crack** had no additional detriment effect on corrosion.
- From on the results presented herein, the **best performance** was found in binders containing 40% FA in combination with 25 L/m^3 CNI at all W/CM ratios studied.

Questions?

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