Performance of Corrosion Inhibiting Admixtures in a Marine Environment

Ian N. Robertson

Craig Newtson

and

Many, many students

Funding provided by:

US Federal Highway Administration

and HI-DOT Research Board, Harbors Division

Twenty-First Annual Westford Symposium on Building Science July 31, 2017

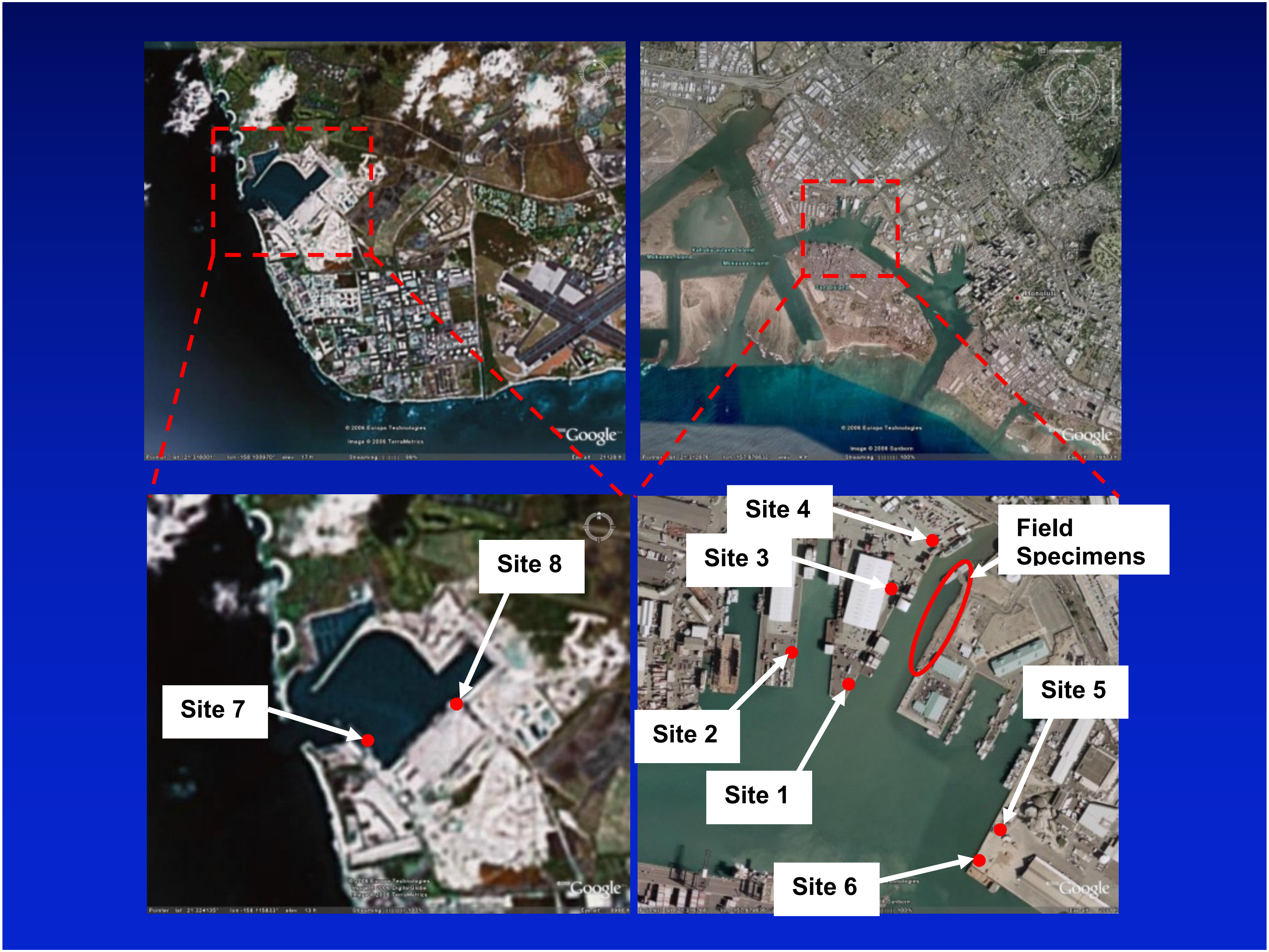
Kauai Hindu Temple
1000-year design life.

Project Timeline

- Initiated in 1998 by Craig Newtson
- Funded for 5 years by FHWA and Hi-DOT (‘98-’03)
- Phase I – Field study of existing piers
- Phase II – Laboratory study of corrosion inhibitors
- Newtson left for New Mexico State Univ. (2003)
- Additional funding for 5 year field deployment (‘04-’09)
- Phase III – Field study of promising inhibitors
- Phase II and III studies terminated in 2012

Project Objectives

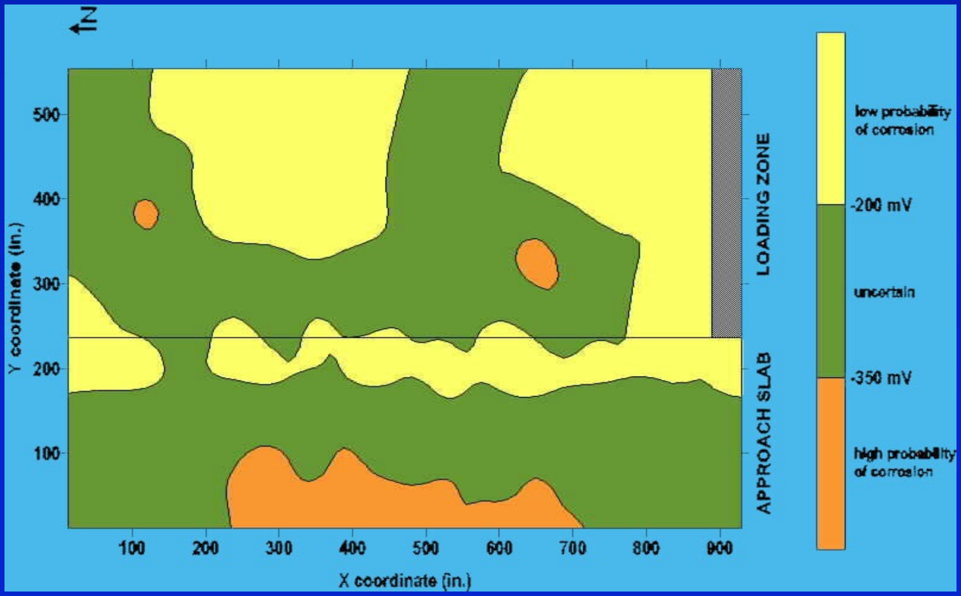
- Phase I – Field testing at harbor piers to evaluate the effectiveness of corrosion-inhibiting measures used in Hawaii
- Phase II – Accelerated Laboratory testing to evaluate the effectiveness of proposed corrosion-inhibiting methods
- Phase III - Compare corrosion-inhibiting methods under field conditions

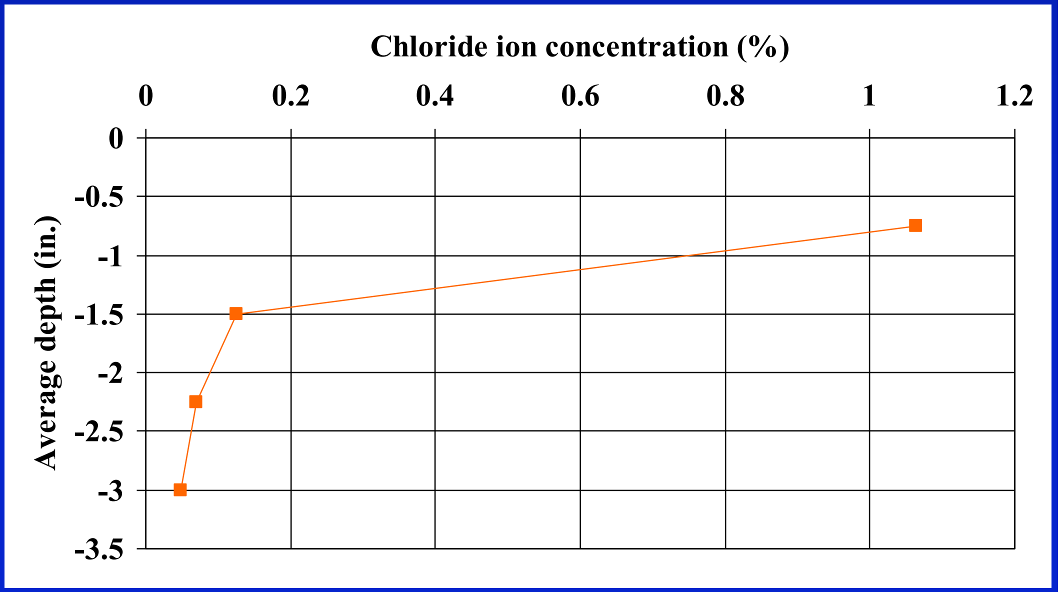

Site 7
Site 8
Site 4
Site 3
Field Specimens
Site 2
Site 1
Site 5
Site 6

Phase I

Field Testing of Existing Piers

- Performed in 2000 by Craig Newtson and Merioni Bola





Phase I - Conclusions

- Corrosion was identified on all piers
- Increased DCI dosage decreased corrosion activity
- Epoxy coated reinforcing bars appeared to effectively combat corrosion

Research Report UHM/CE/00-01
by Bola and Newtson
Available at:

www.cee.hawaii.edu

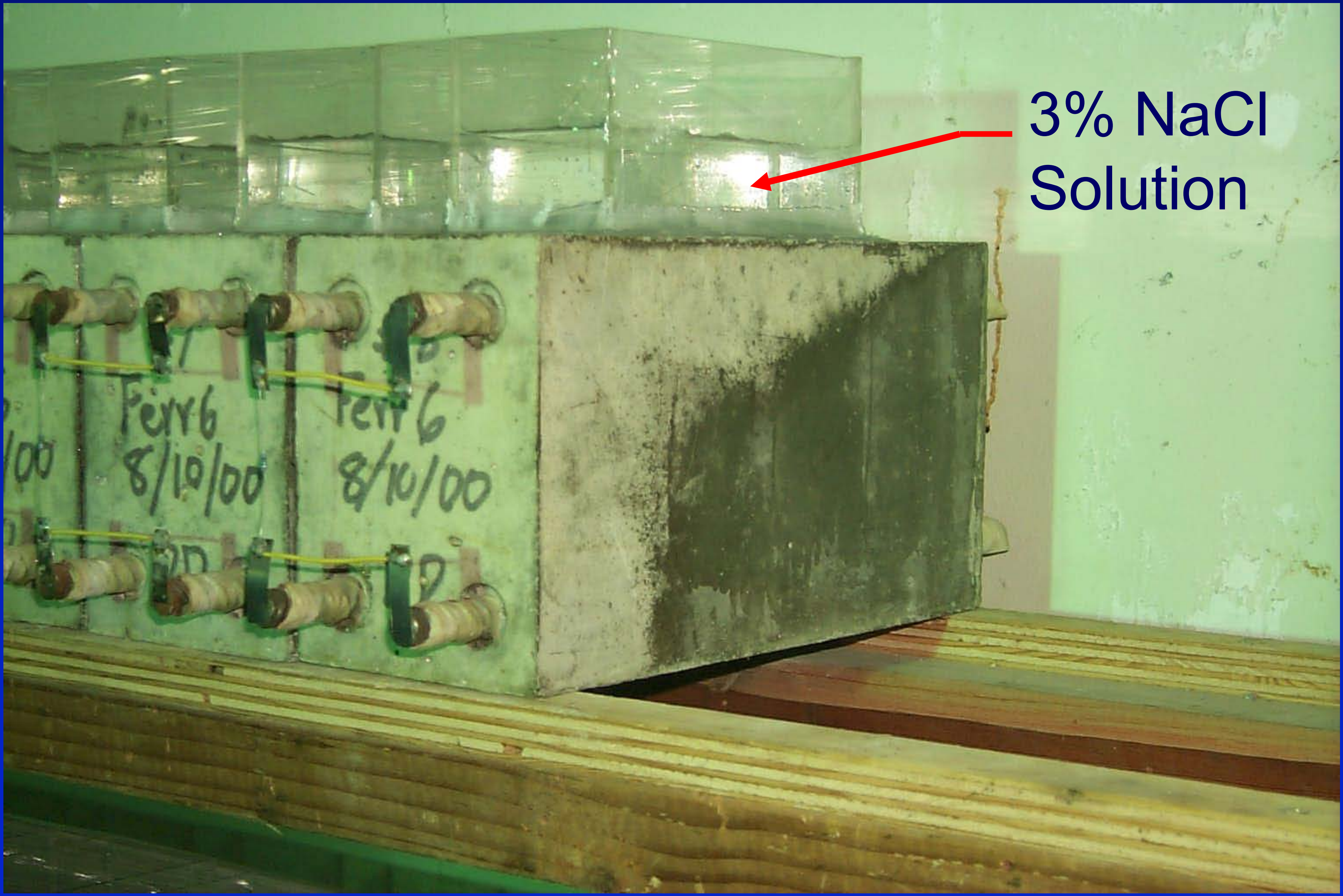
Corrosion Inhibitor Study

- Phase II: Accelerated Laboratory corrosion tests
- Phase III: Field Exposure specimens
- Field study results
- Conclusions
- Recommendations

Phase II - Laboratory Testing

- Accelerated Laboratory corrosion tests – modified ASTM G 109-92
- Evaluating various corrosion inhibiting measures

Typical ASTM G 109 Test Specimen



3% NaCl
Solution

Specimen Variables

- Water-Cementitious Material Ratio

  0.35 0.40 0.45
- Aggregates

  Halawa and Kapaa
- Paste Content
  - Varied from 28% to 35%
- Admixtures
  - Control specimens with no admixtures
  - Specimens with each of 8 admixtures intended to inhibit corrosion
- Reinforcing Steel
  - Uncoated Grade 60 deformed bars

Admixtures

- DAREX Corrosion Inhibitor (DCI)
- Rheocrete CNI
- Rheocrete 222+
- FerroGard 901
- Xypex Admix C-2000
- Latex-Modifier
- Silica Fume
- Fly Ash

UH Structures Laboratory Basement

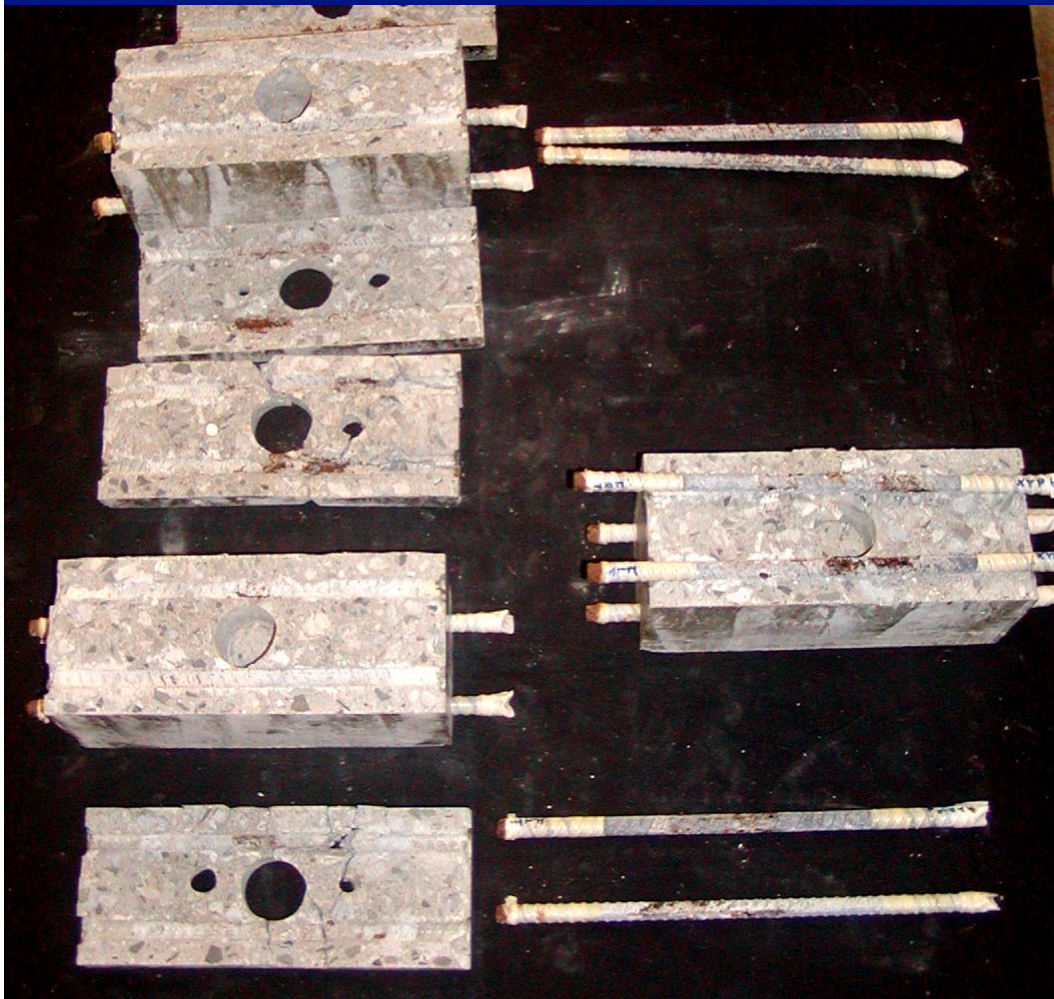
100 different concrete mixtures

656 Individual specimens

Test Procedures

- Material Properties
  - Compressive Strength
  - Elastic Modulus
  - Permeability
- Initial and Final Conditions
  - Chloride Concentration Analysis
  - pH
- Readings every wet/dry cycle
  - Corrosion Current
  - Half-Cell Potential
  - Linear Polarization Resistance
  - Concrete Resistivity
- Autopsy
  - Split specimen at top reinforcement
  - Record extent of corrosion

Specimen Autopsy



- Record exterior appearance
- Half-cell readings over top reinforcement
- Core center of specimen
- Slice and grind samples for chloride tests at 0.5", 1", 1.5" and 2" below top surface
- Split at top reinforcement
- Record extent of corrosion
- pH measurement at top steel
- Discard specimen
- Repeat – 656 times!

Laboratory Phase

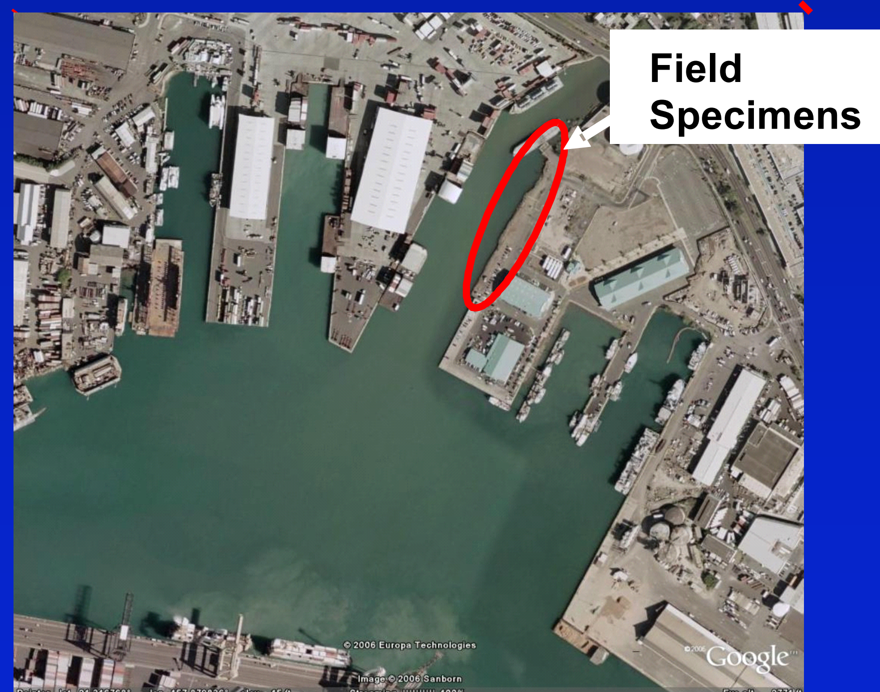
- All specimens autopsied and recorded
- Two published reports
  - Kakuda, Robertson and Newtson (2005) UHM/CEE/05-04
  - Okunaga, Robertson and Newtson (2005) UHM/CEE/05-05

Laboratory Observations

- Low w/c ratio meant that many specimens took longer than expected to corrode
- Reinforcement protection admixtures:
  - DCI and CNI show effective protection
  - Rheocrete 222+ and FerroGard 901 show unreliable performance
- Decreased permeability admixtures:
  - Flyash and Silica Fume both effective
  - Xypex Admix C-2000 and Latex-Modifier performed poorly

Long-Term Field Monitoring

- 25 Field panels were placed at mean sea level at Pier 38 in Honolulu Harbor
- Selected most promising Phase II mixtures
- Included one panel with Kryton KIM
- Panels installed from July 2002 to June 2003
- Measurements to be taken annually for 7 years - supported by HDOT funding

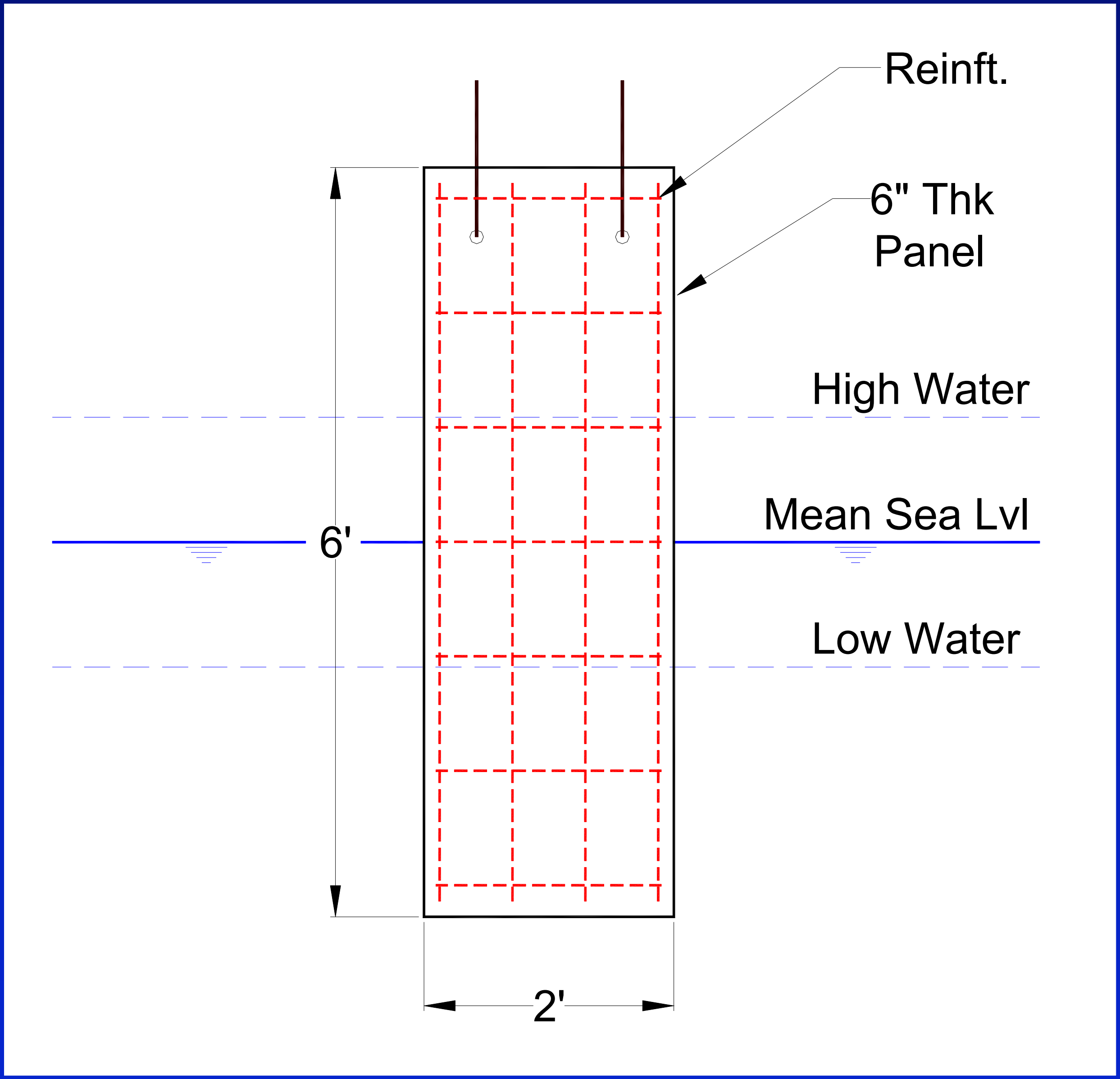


Honolulu

Field Site

Oahu, Hawaii

Long-Term Field Specimen Design

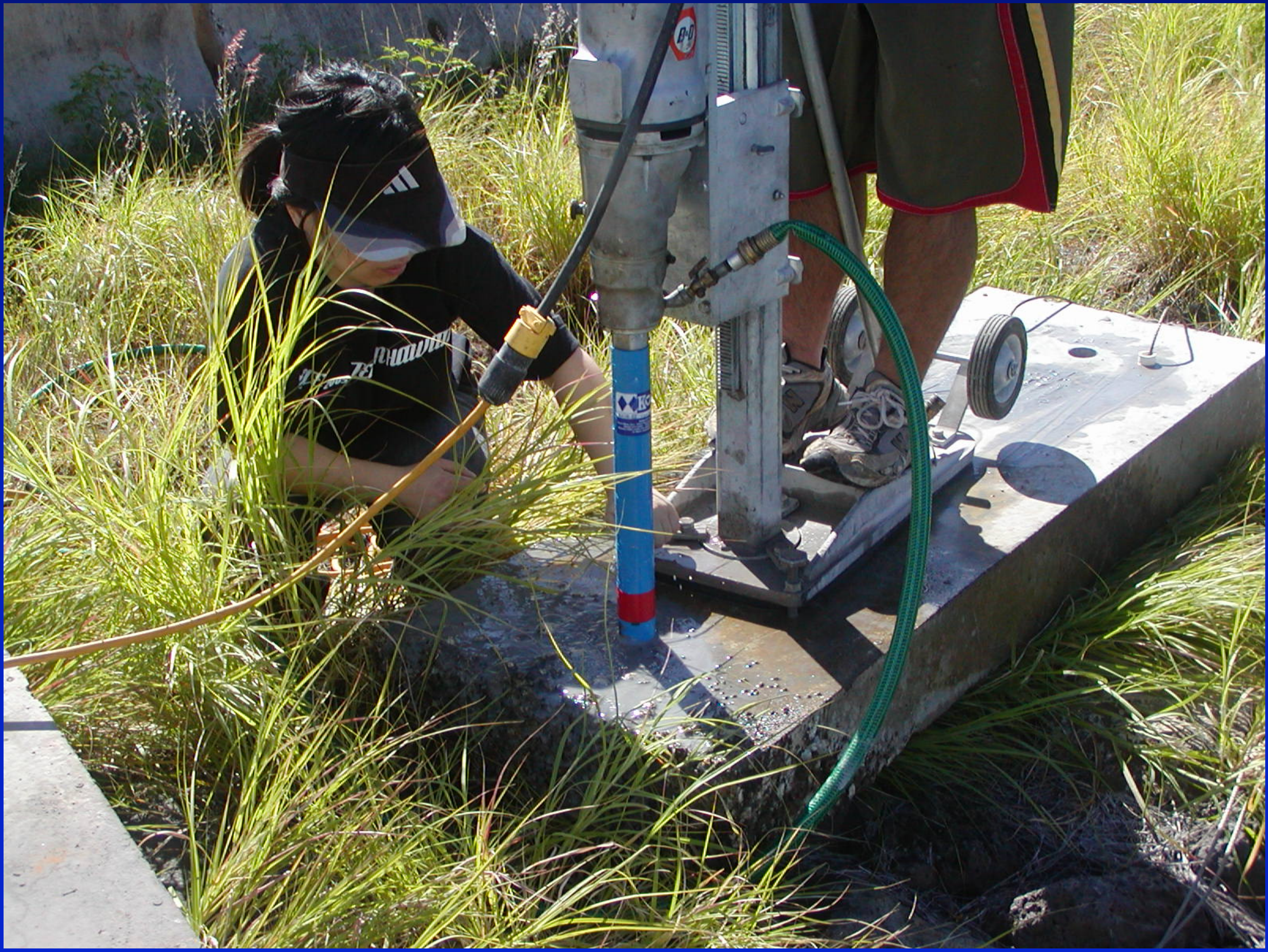


Typical Field Panels

Field Specimen Tests

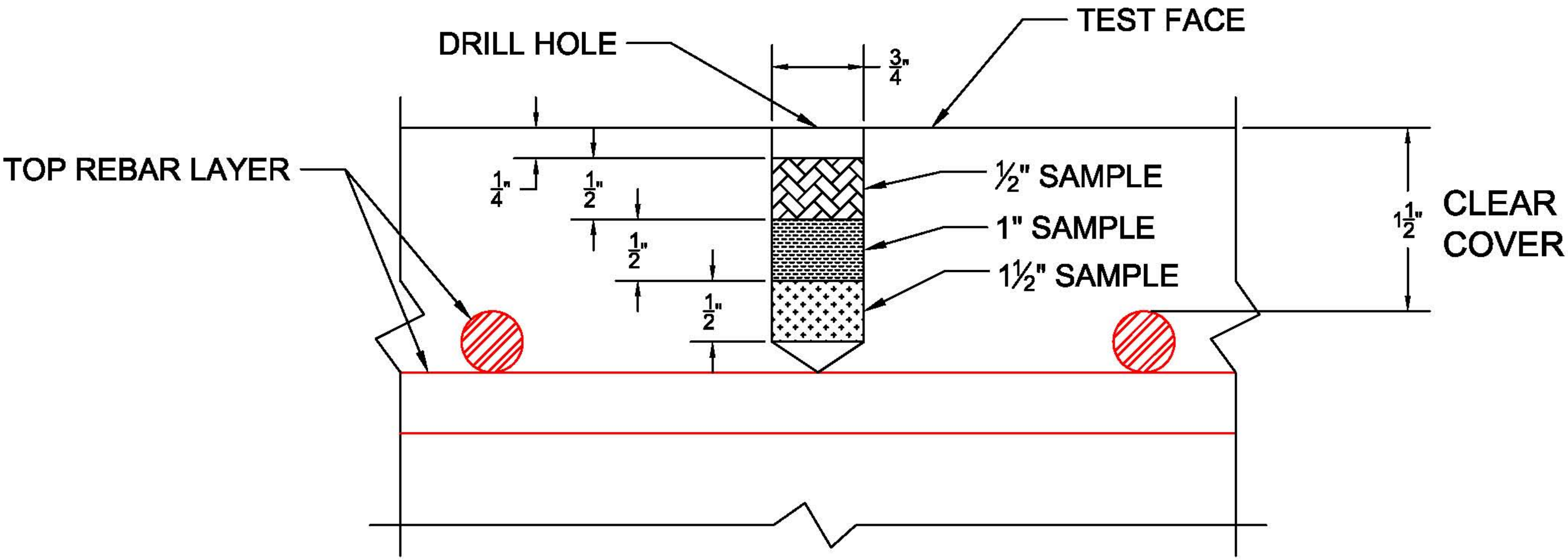
- Half-cell potential readings taken across top surface of panel - annually
- Panels removed from ocean every other year
- Chloride concentrations taken through cover concrete (away from the reinforcing steel)
- pH levels measured at level of reinforcing

Bi-Annual Data Collection



Chloride Concentration Samples

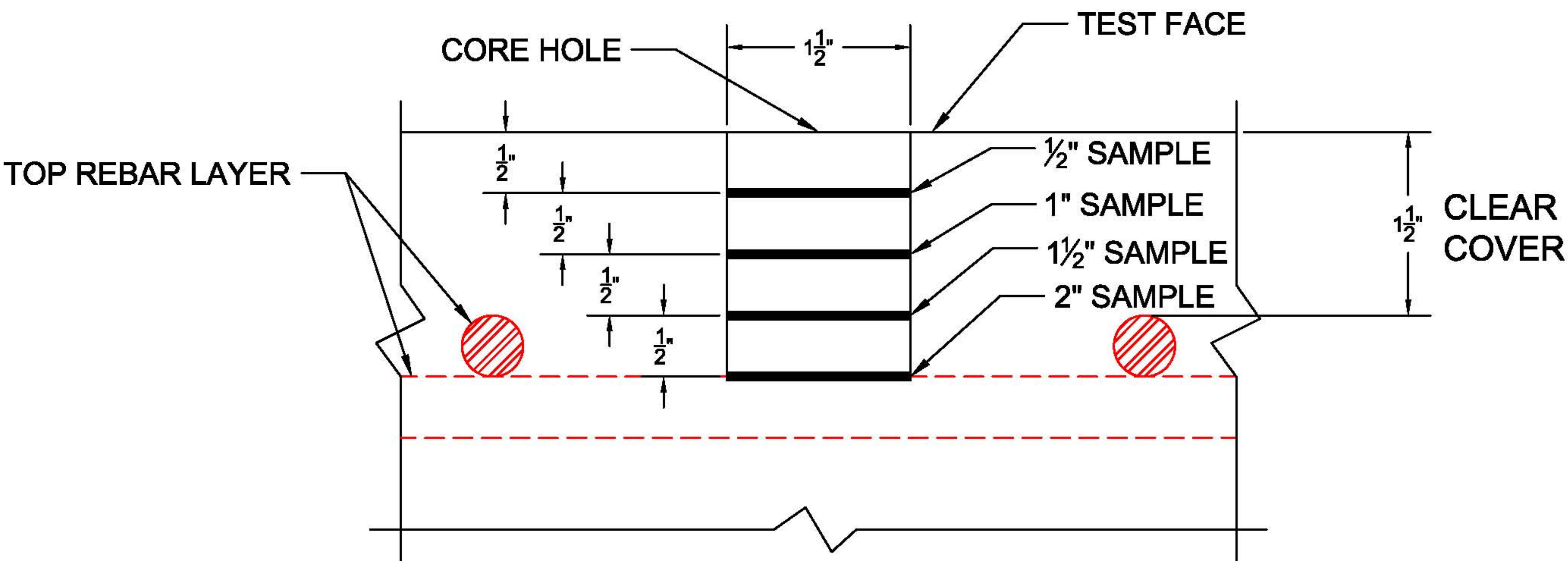
2004 concrete sampling method



Chloride Concentration Samples

2006, 2008, 2010, 2012

concrete sampling method



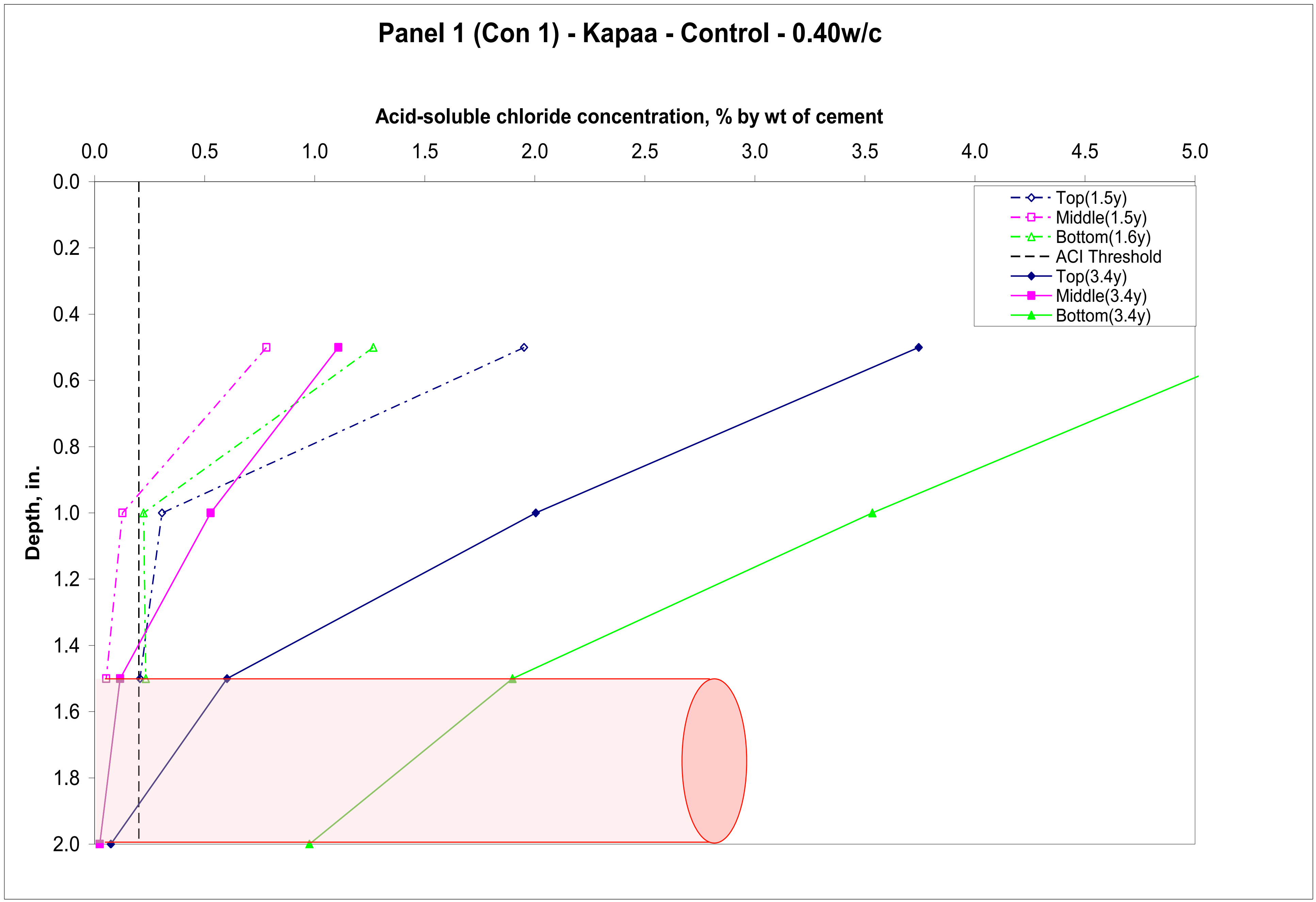
- Field Panel Sampling
  - Extract cores
  - Cut slices at various depths
  - Crush to powder
  - Test for chloride content
  - Test for pH level

Chloride Concentration Tests

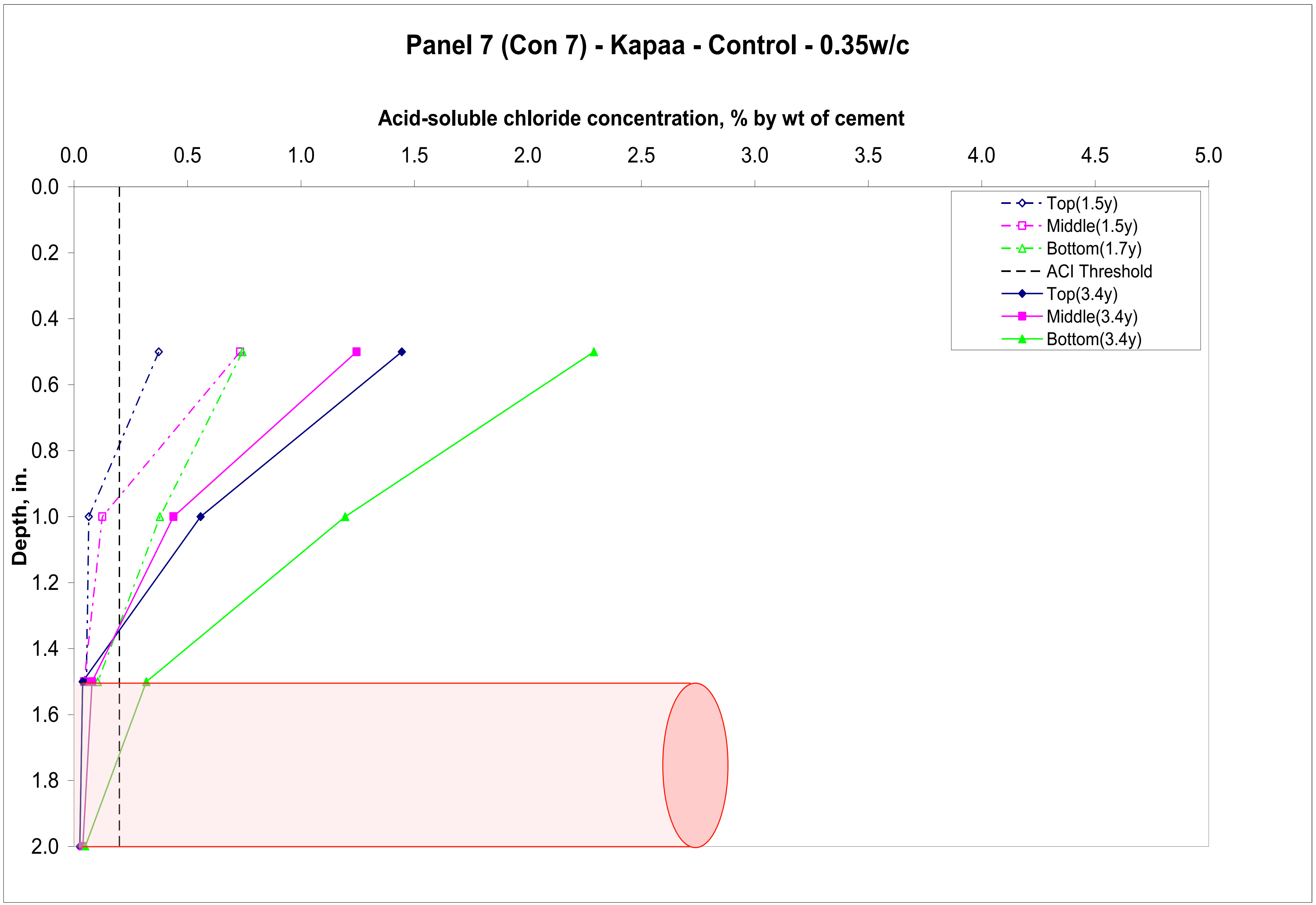
❖All chloride concentrations used the **Acid-Soluble** test method with a CL-2000 Chloride Field Test System (James Instruments, Inc.)

www.ndtjames.com

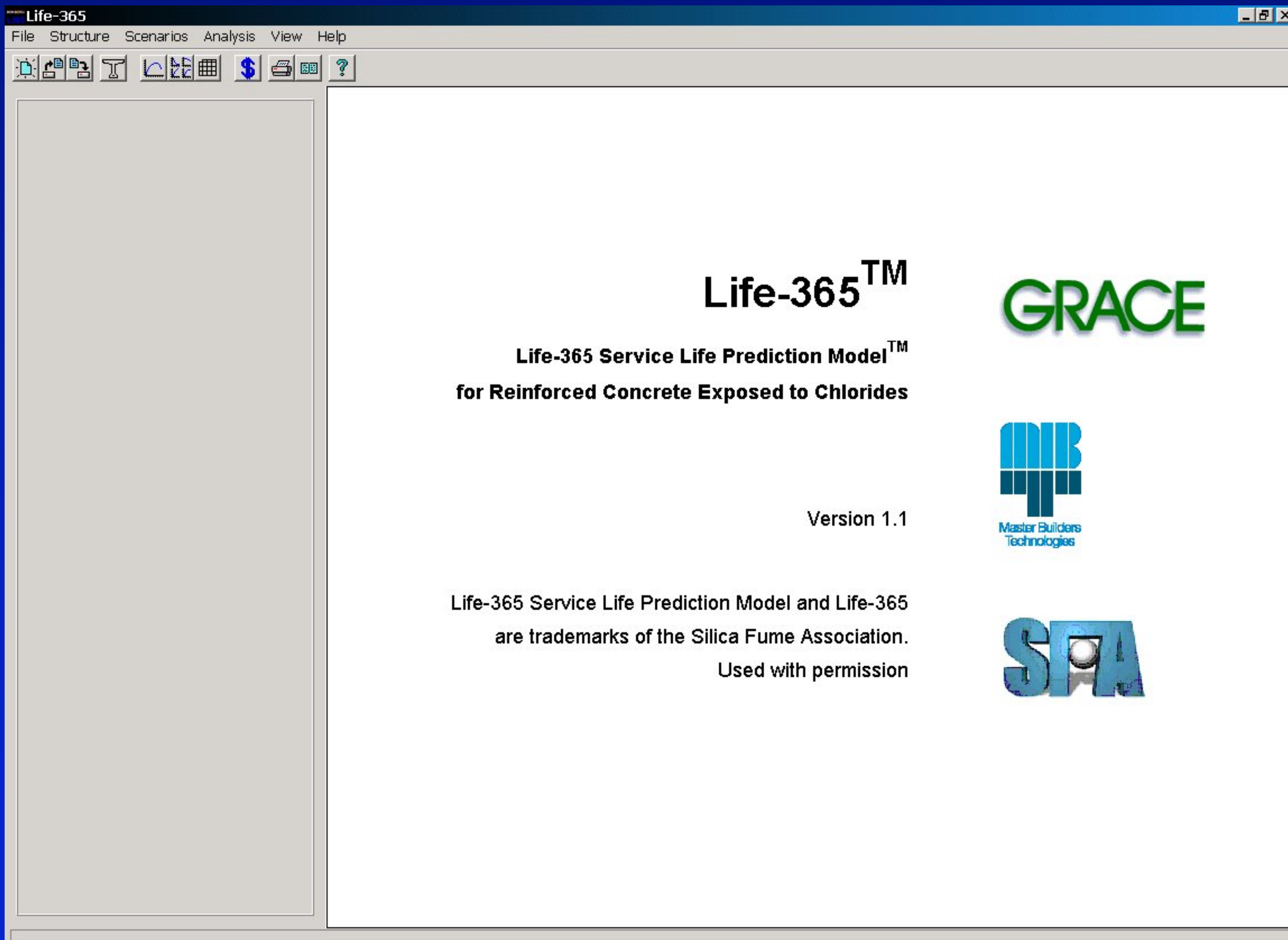
Chloride Concentration v.s. depth for Control w/ 0.40 w/c



Chloride Concentration v.s. depth for Control w/ 0.35 w/c



Life-365 Prediction Software



Life-365 Prediction Software

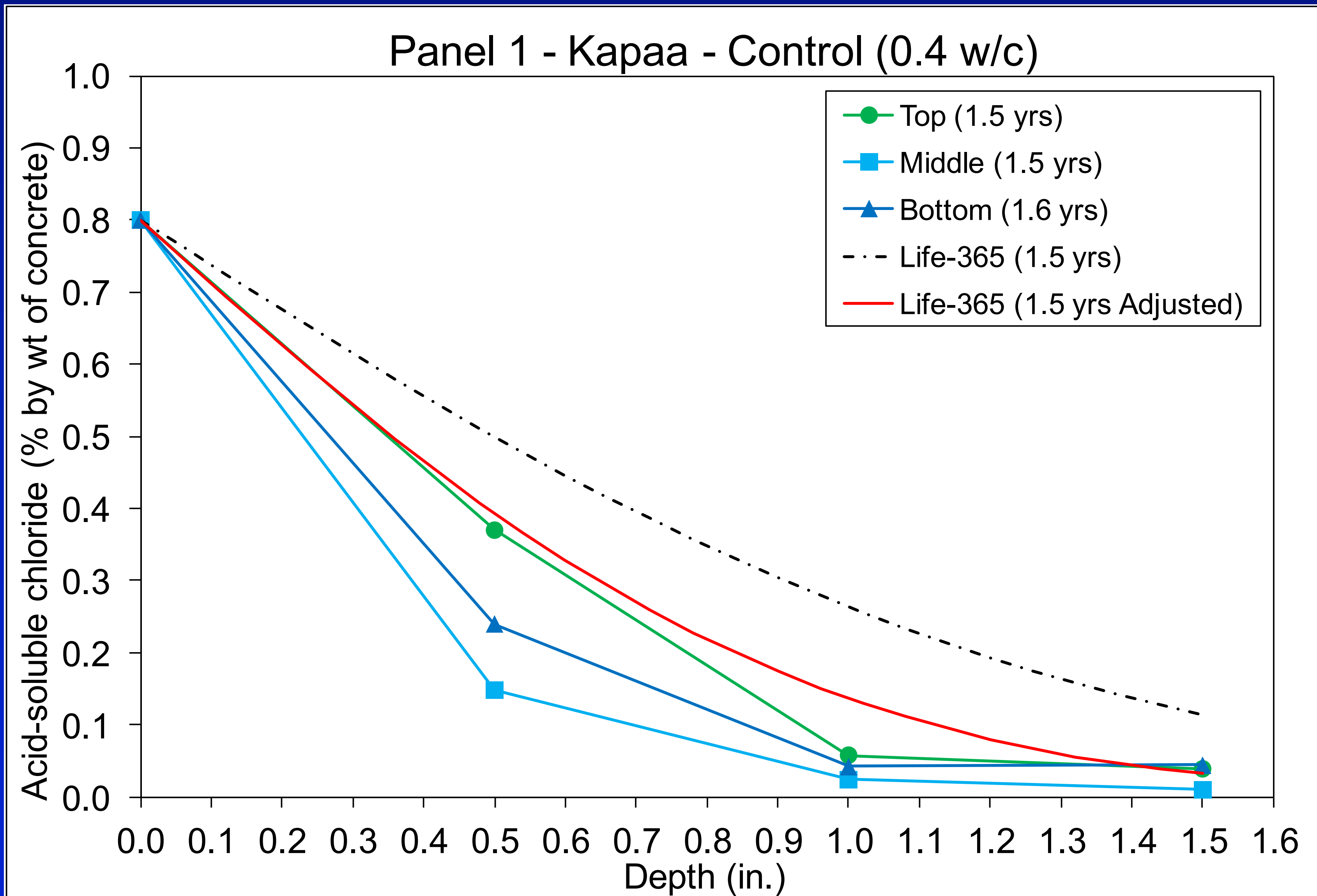
- Admixtures are limited for analysis:
  - Rheocrete CNI (used for DCI also as same calcium nitrite compositions)
  - Rheocrete 222+
  - Fly Ash
  - Silica Fume
  - Slag (not used for this research)

Life-365 Default Values

- The three main values focused on in this report include:

1. Diffusion coefficient, D_{28} (m^2/s)
2. Diffusion decay index, **m** (dimensionless)
3. Chloride threshold, **Ct** (% mass concrete)

Chloride Concentrations with Life-365 Predictions

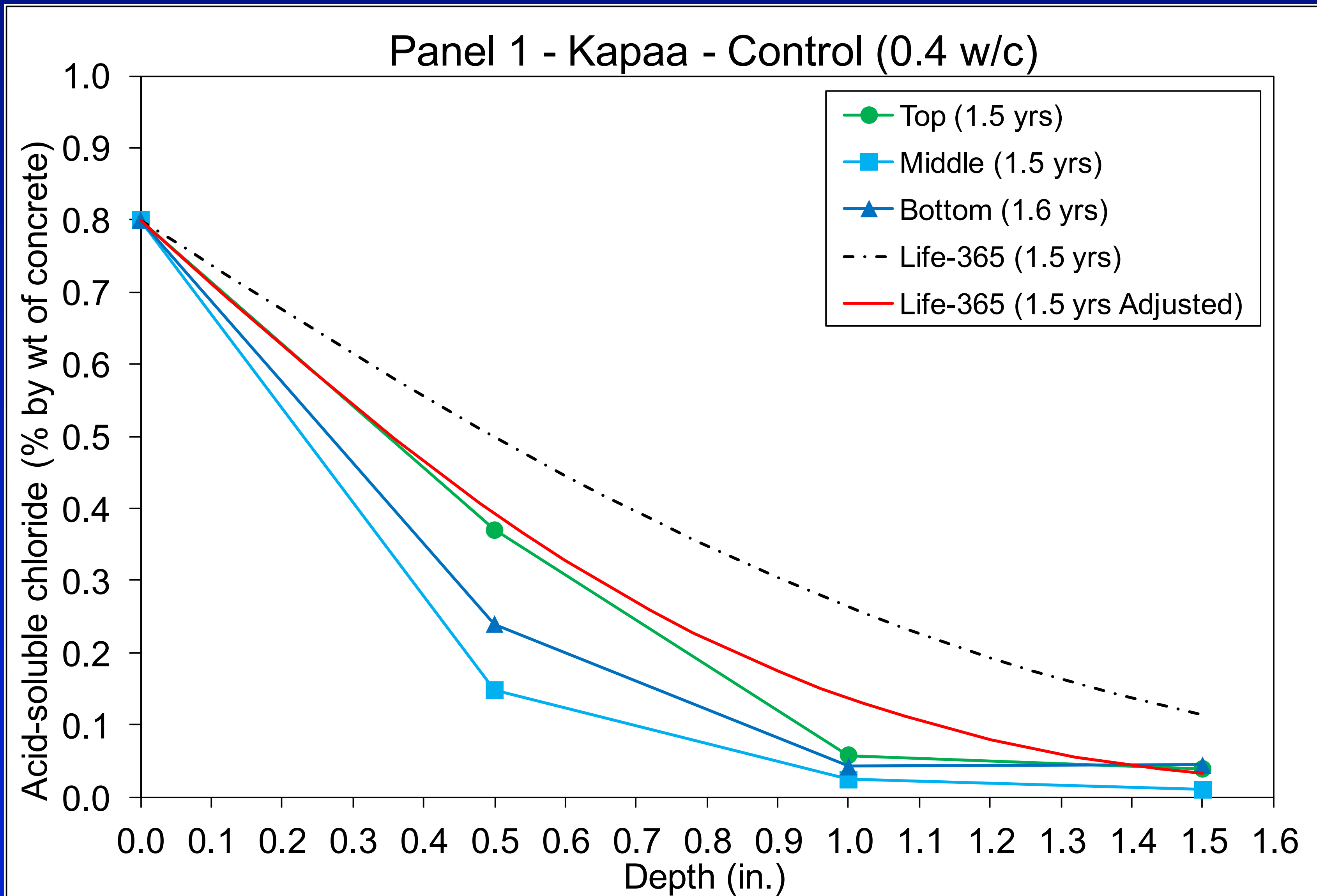


Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for Control Panels 1 and 2

	Default values	Adjusted values
Diffusion coefficient	7.94E-12	5.50E-12
m	0.20	0.38
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



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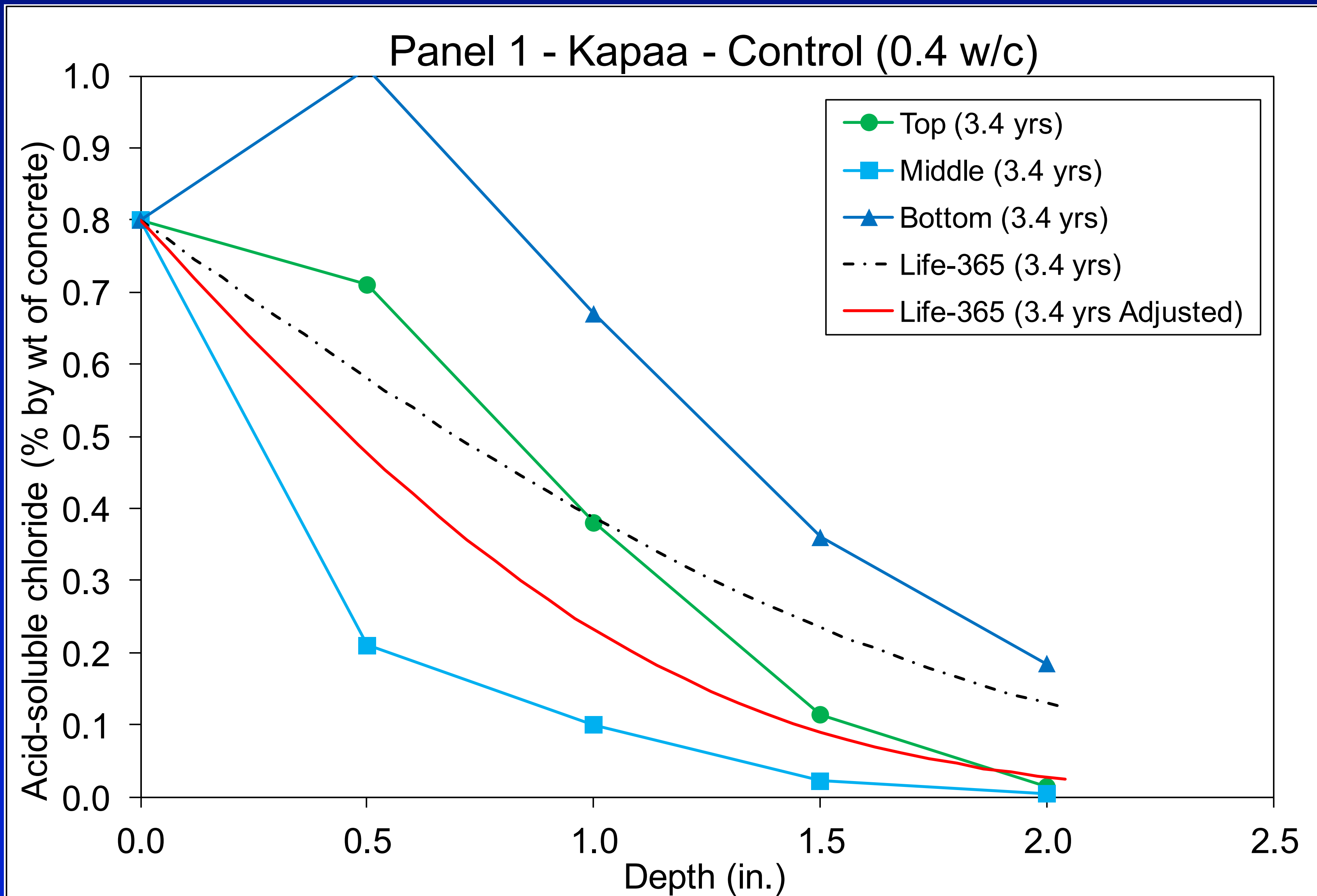
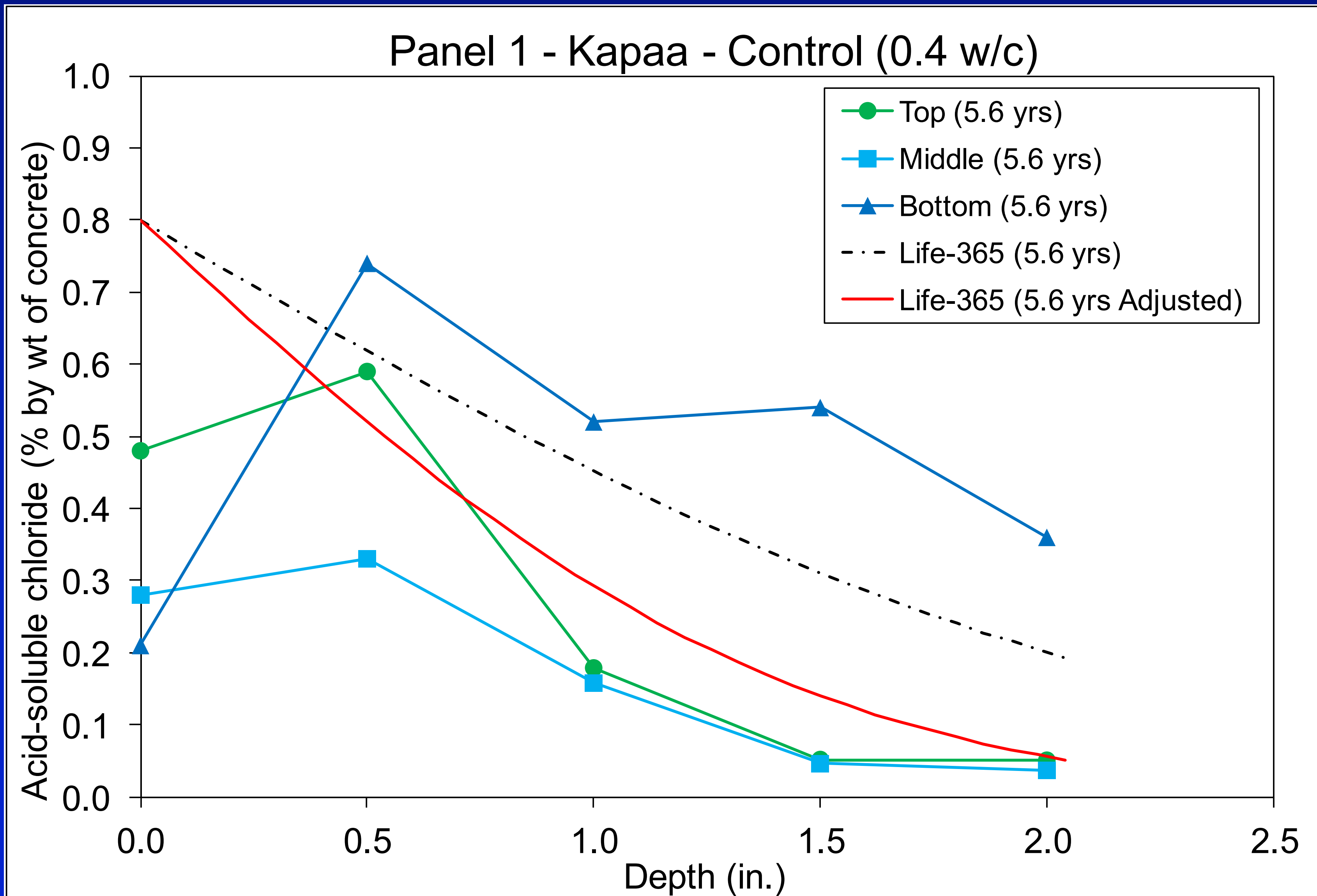
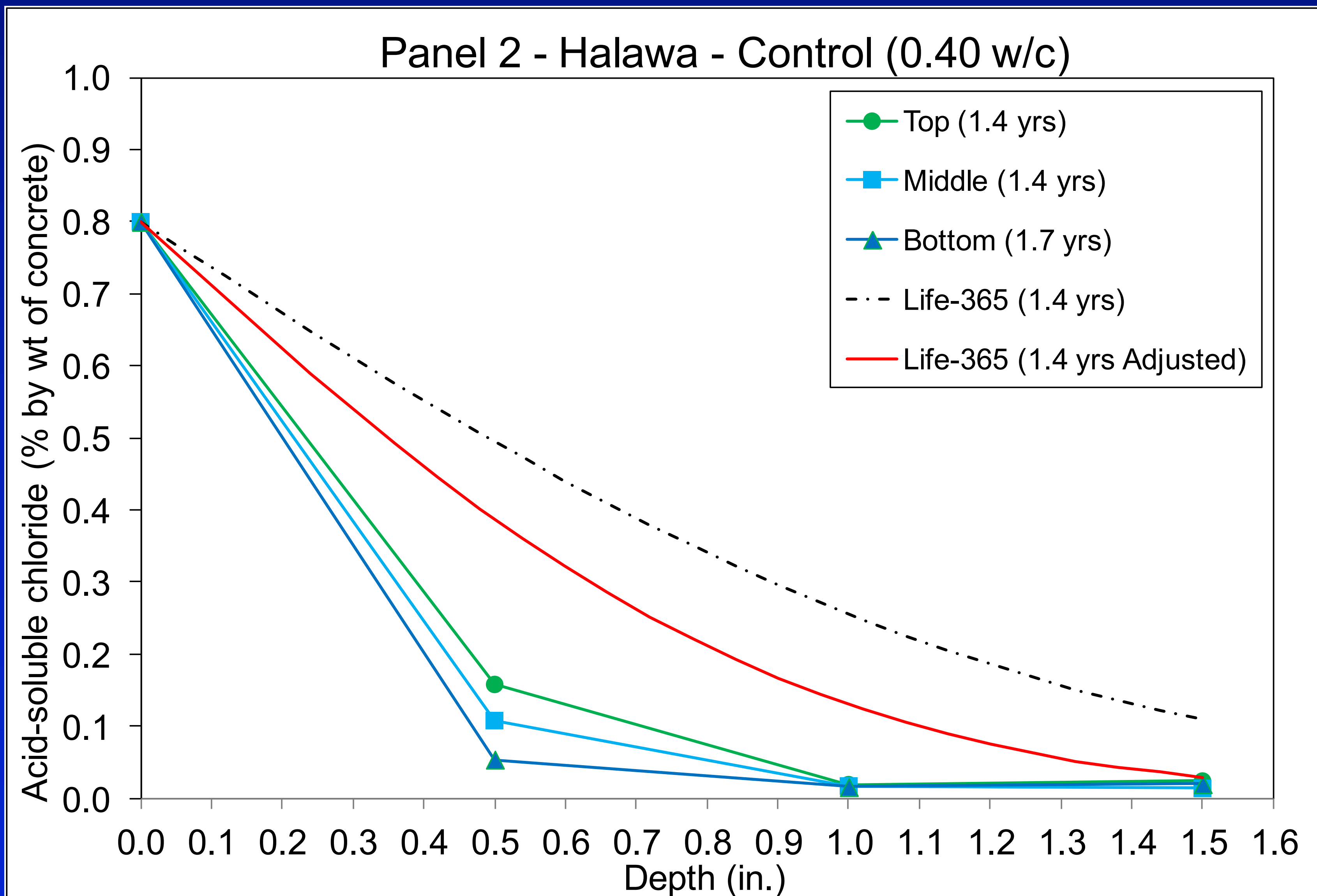


Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions



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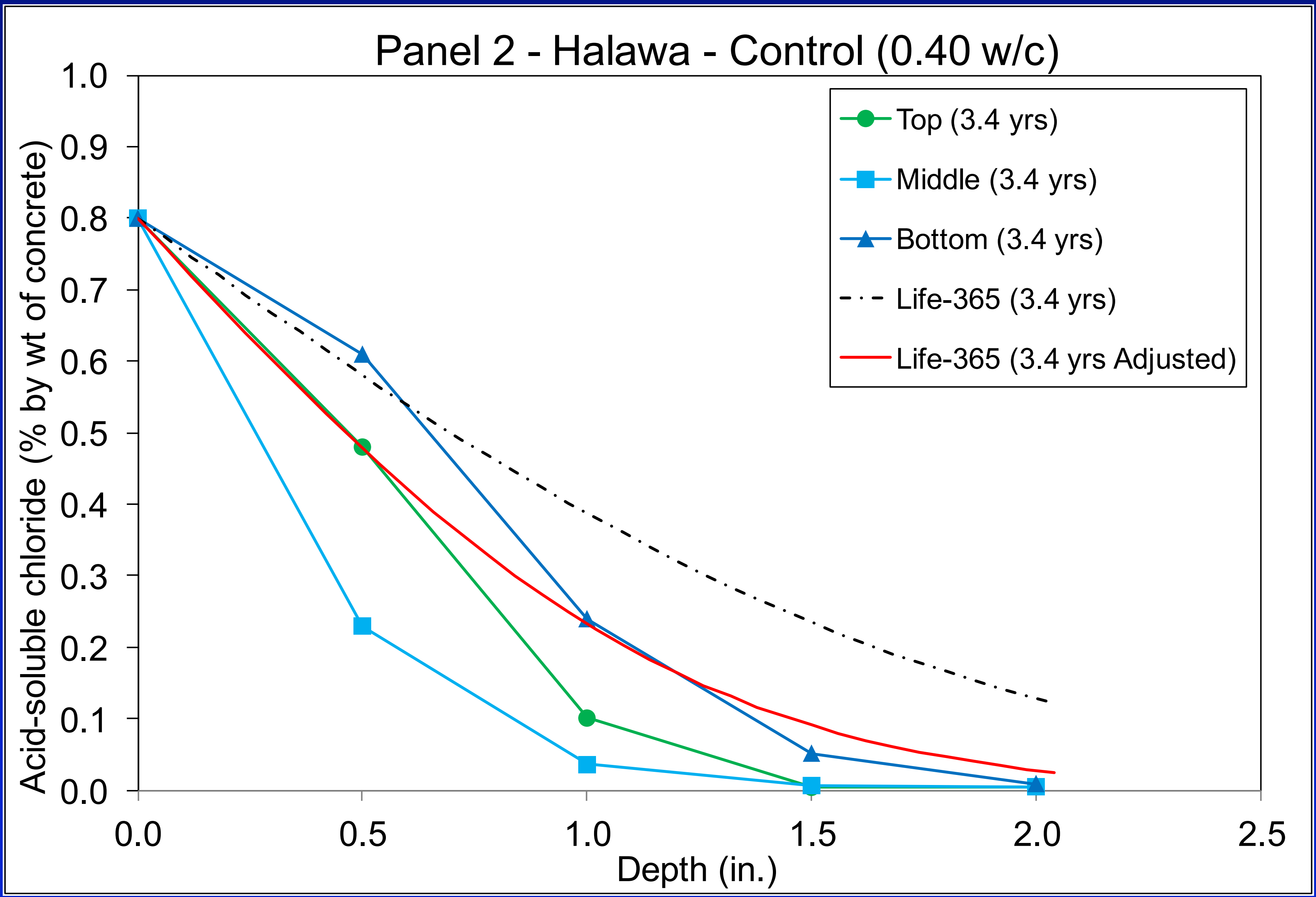
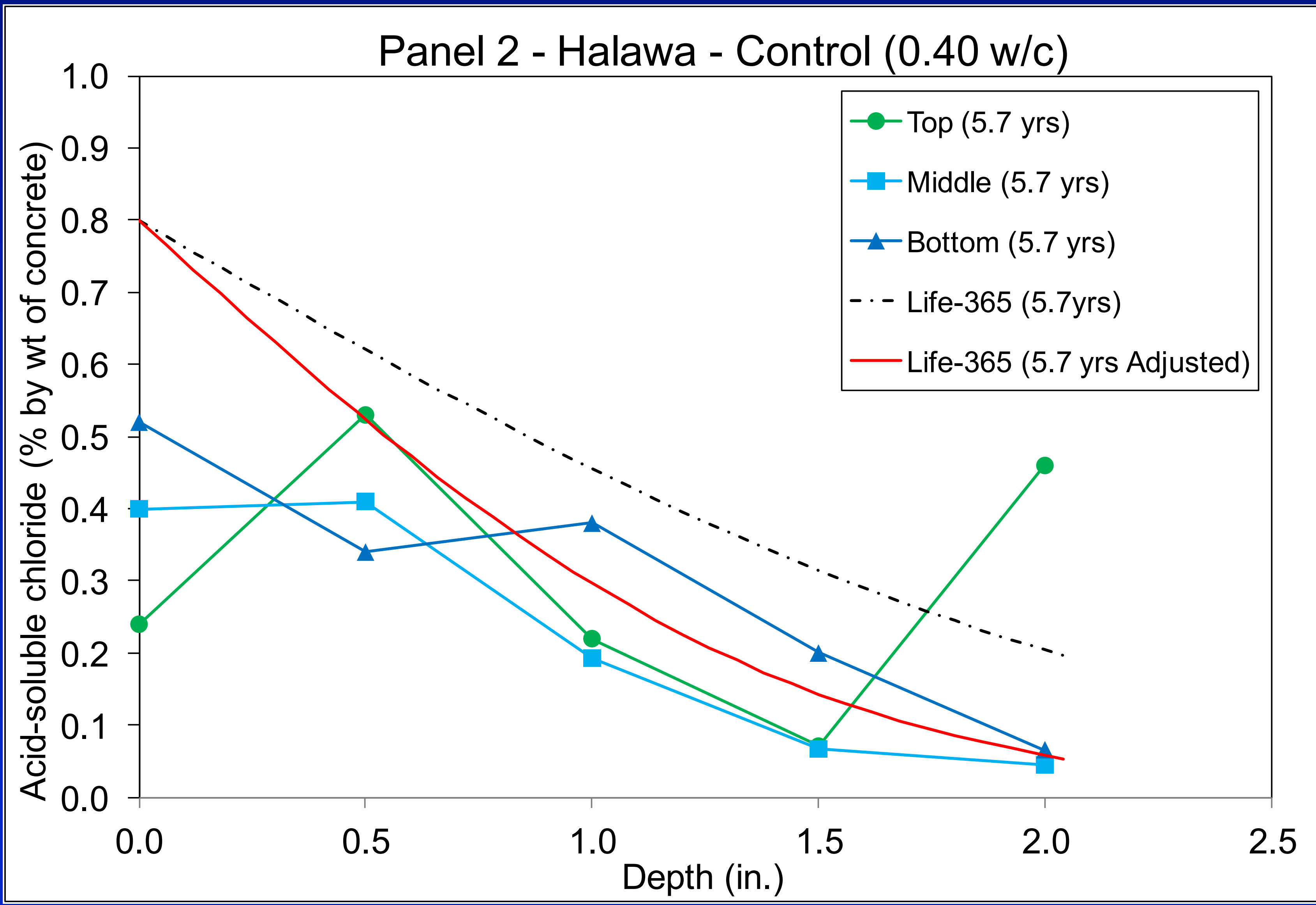


Chloride Concentrations with Life-365 Predictions

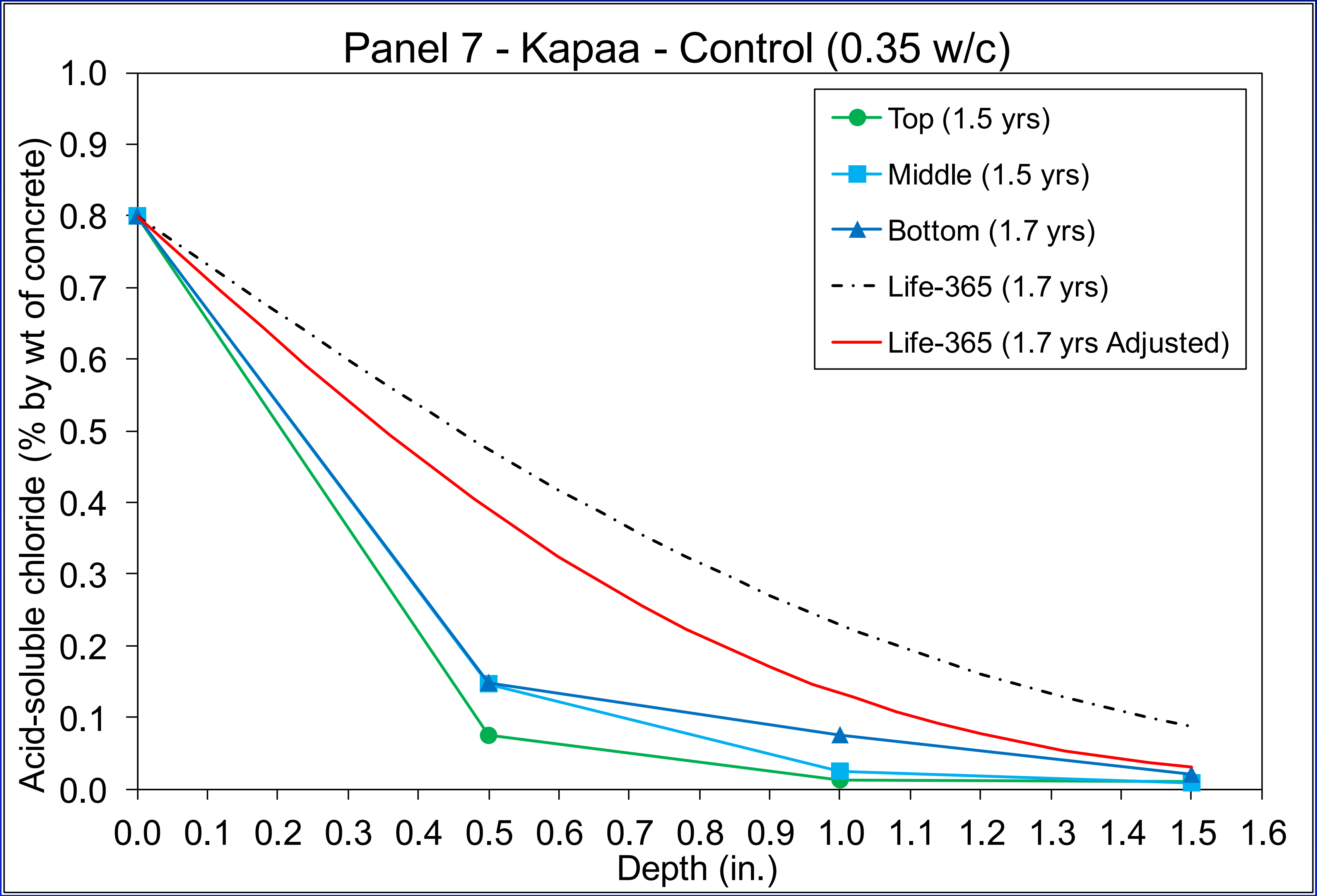


Chloride Concentrations with Life-365 Predictions

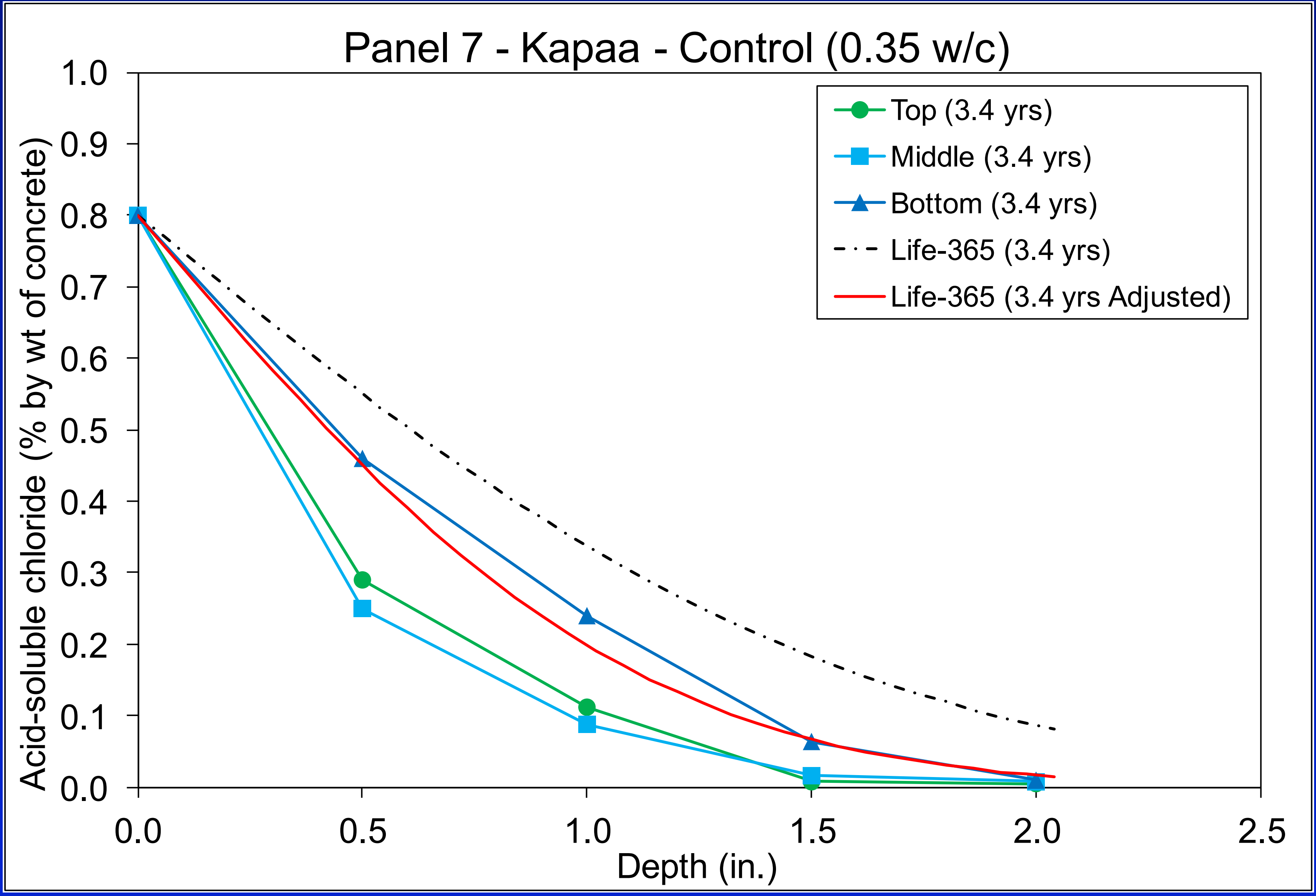
- Default and adjusted input values for Control Panel 7

	Default values	Adjusted values
Diffusion coefficient	6.03E-12	6.50E-12
m	0.20	0.53
Corrosion threshold	0.05	0.05

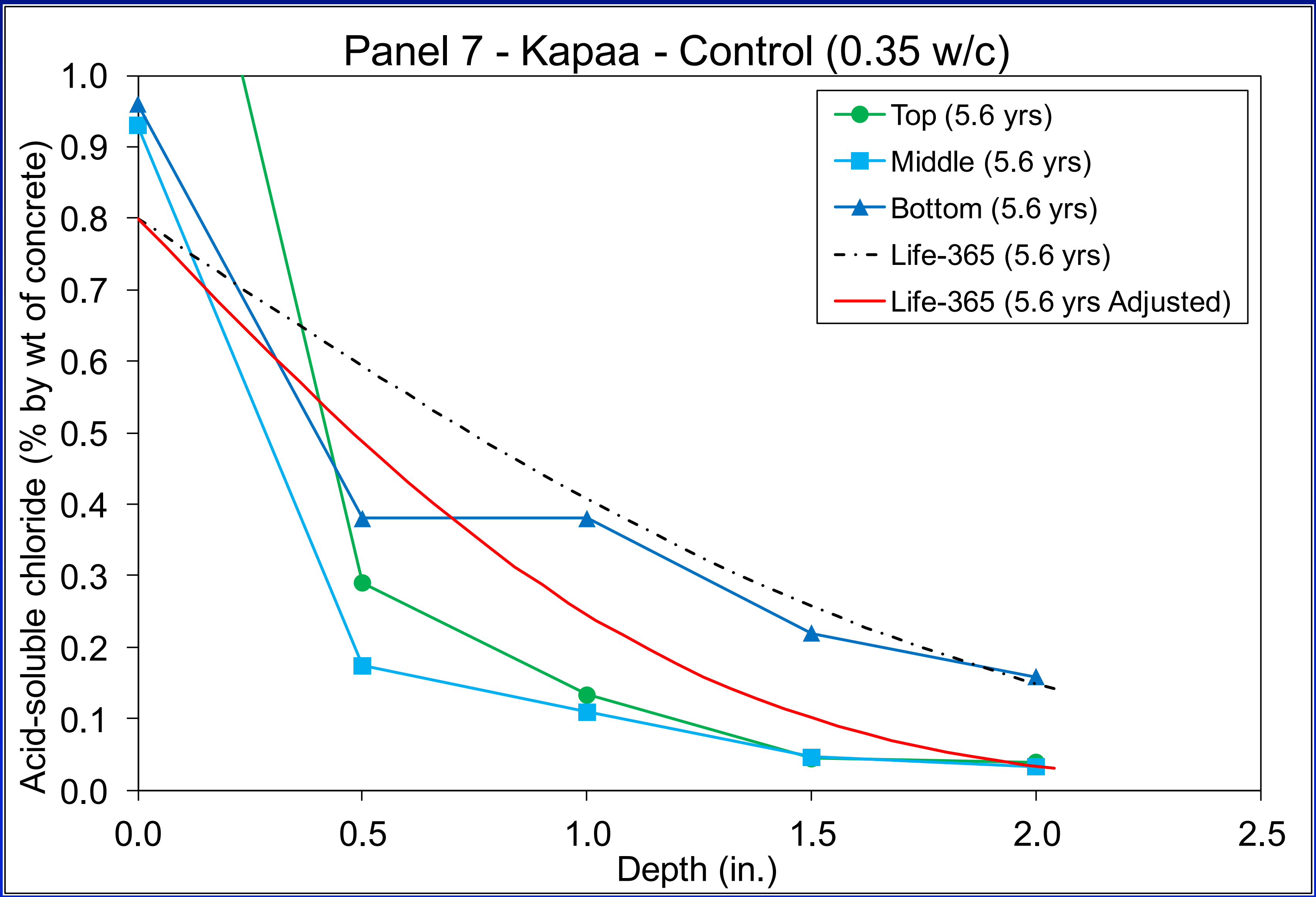
Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions

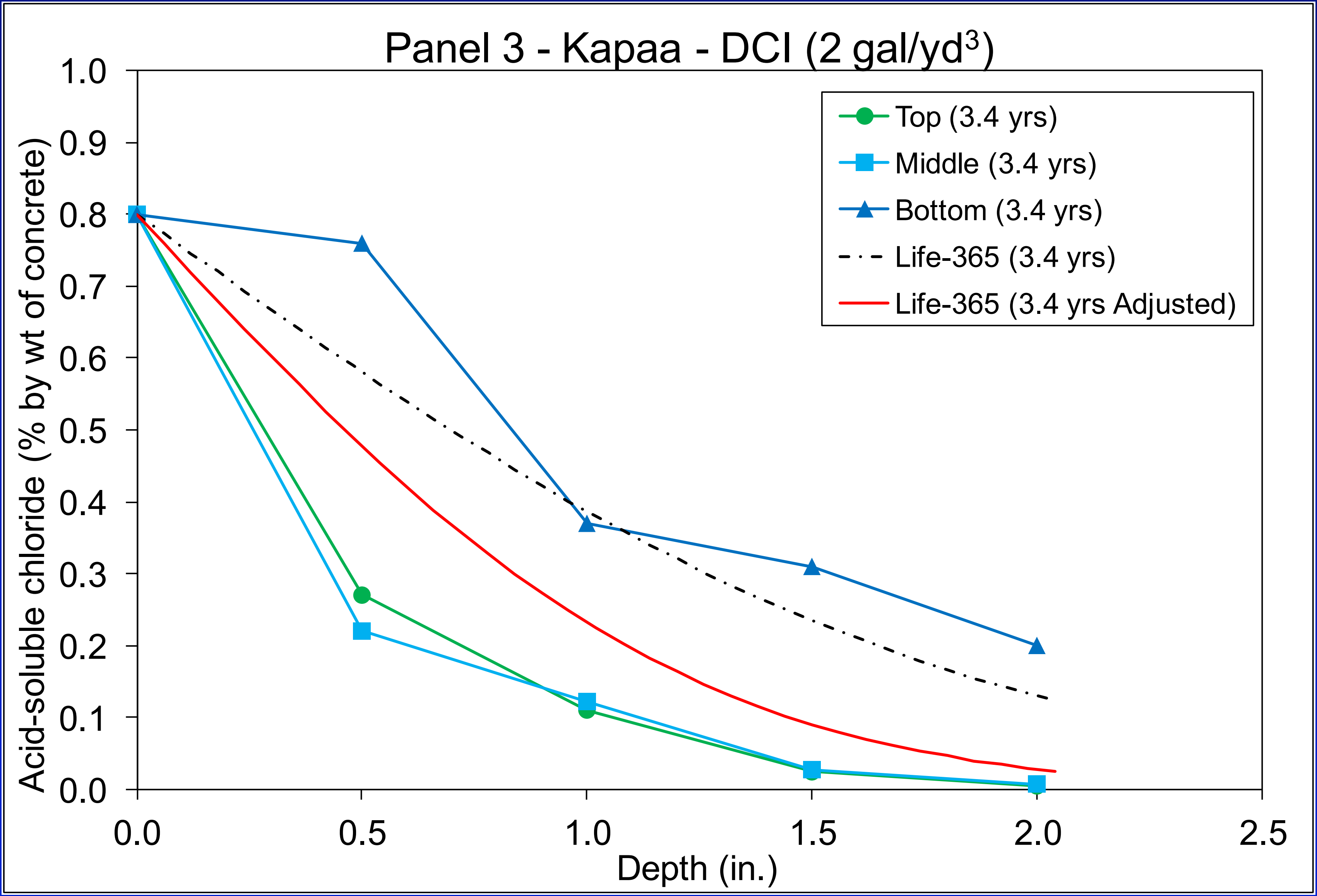


Chloride Concentrations with Life-365 Predictions

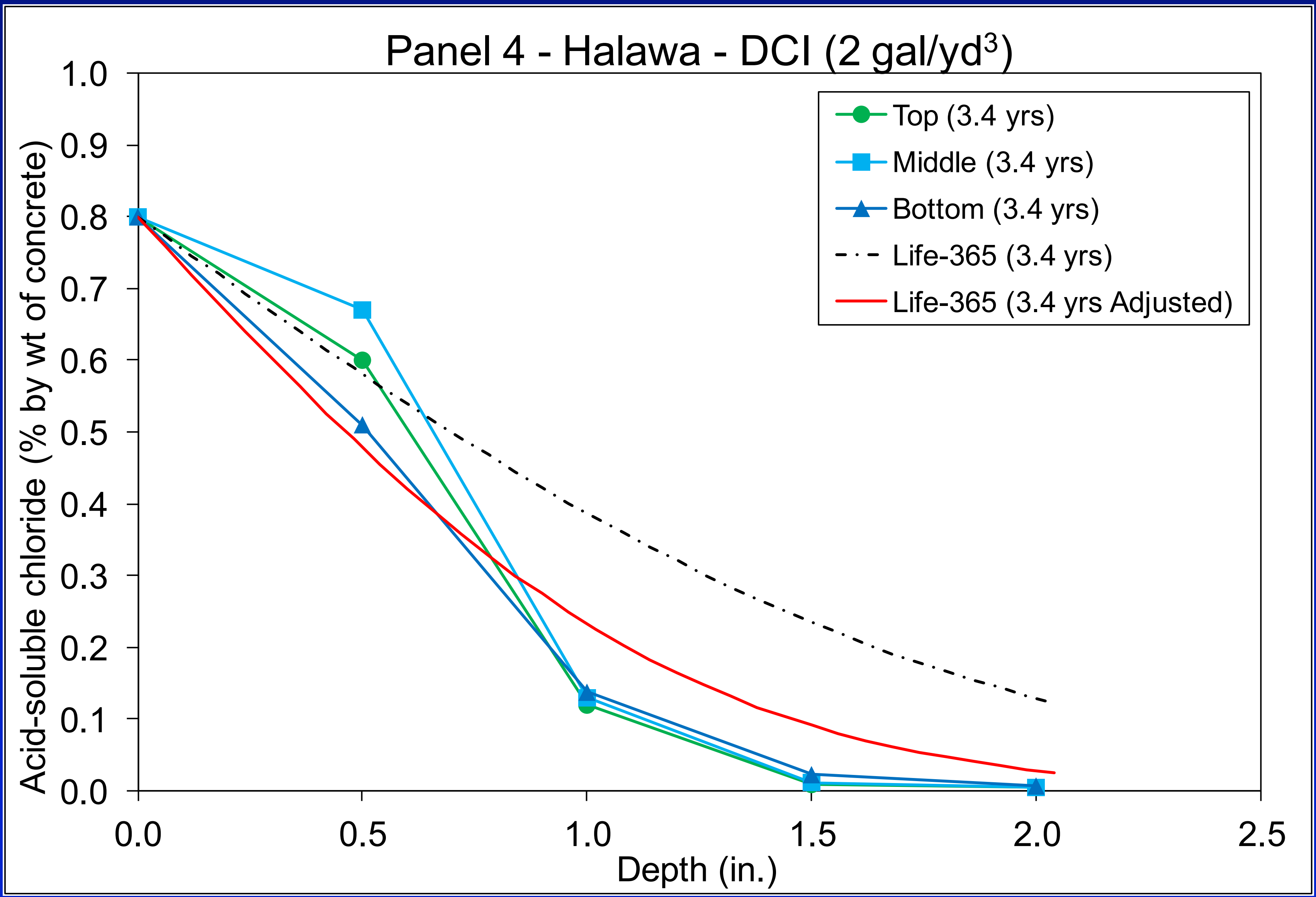
- Default and adjusted input values for DCI Panels

	Default values	Adjusted values
Diffusion coefficient	7.94E-12	5.50E-12
m	0.20	0.38
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions

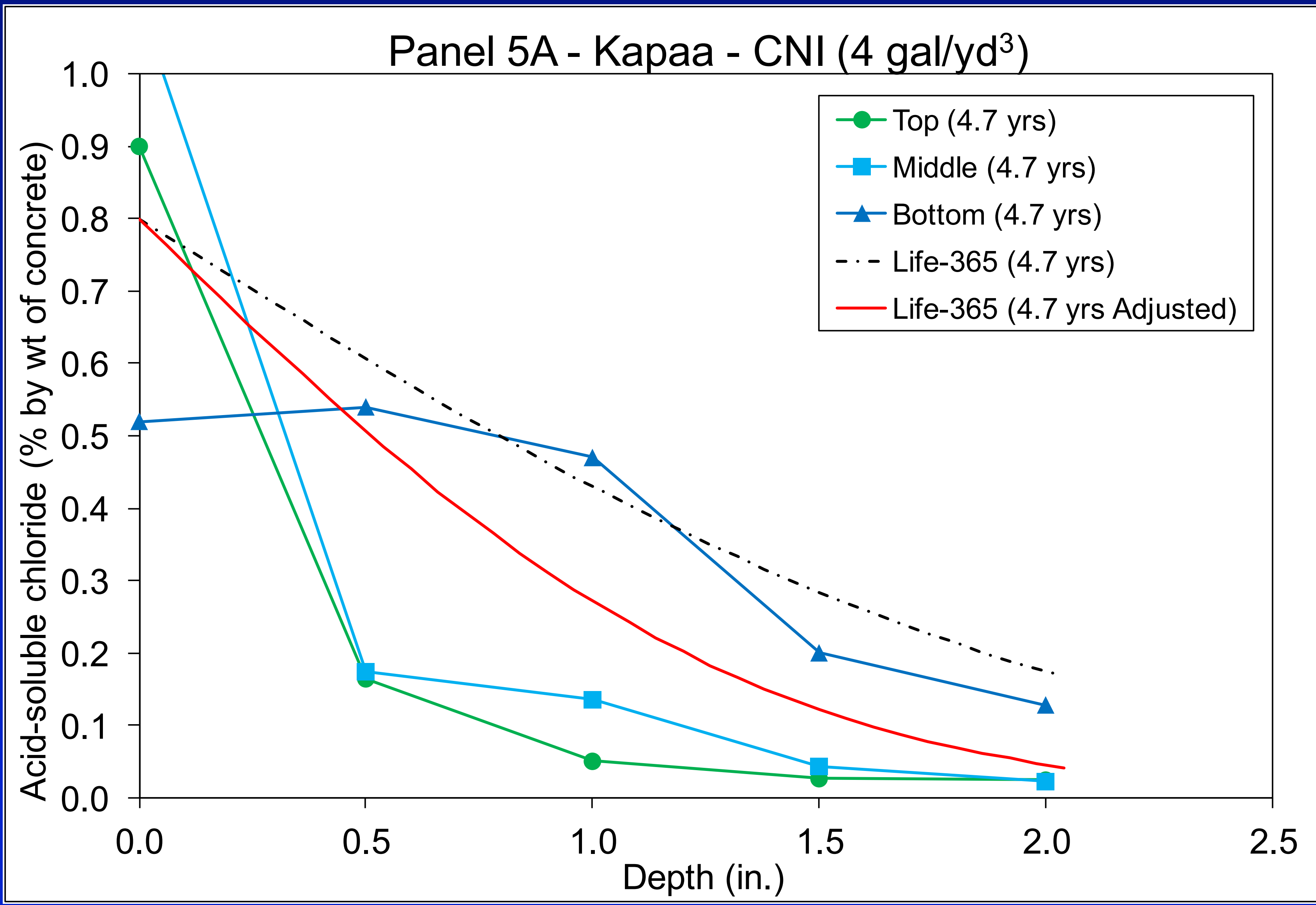


Chloride Concentrations with Life-365 Predictions

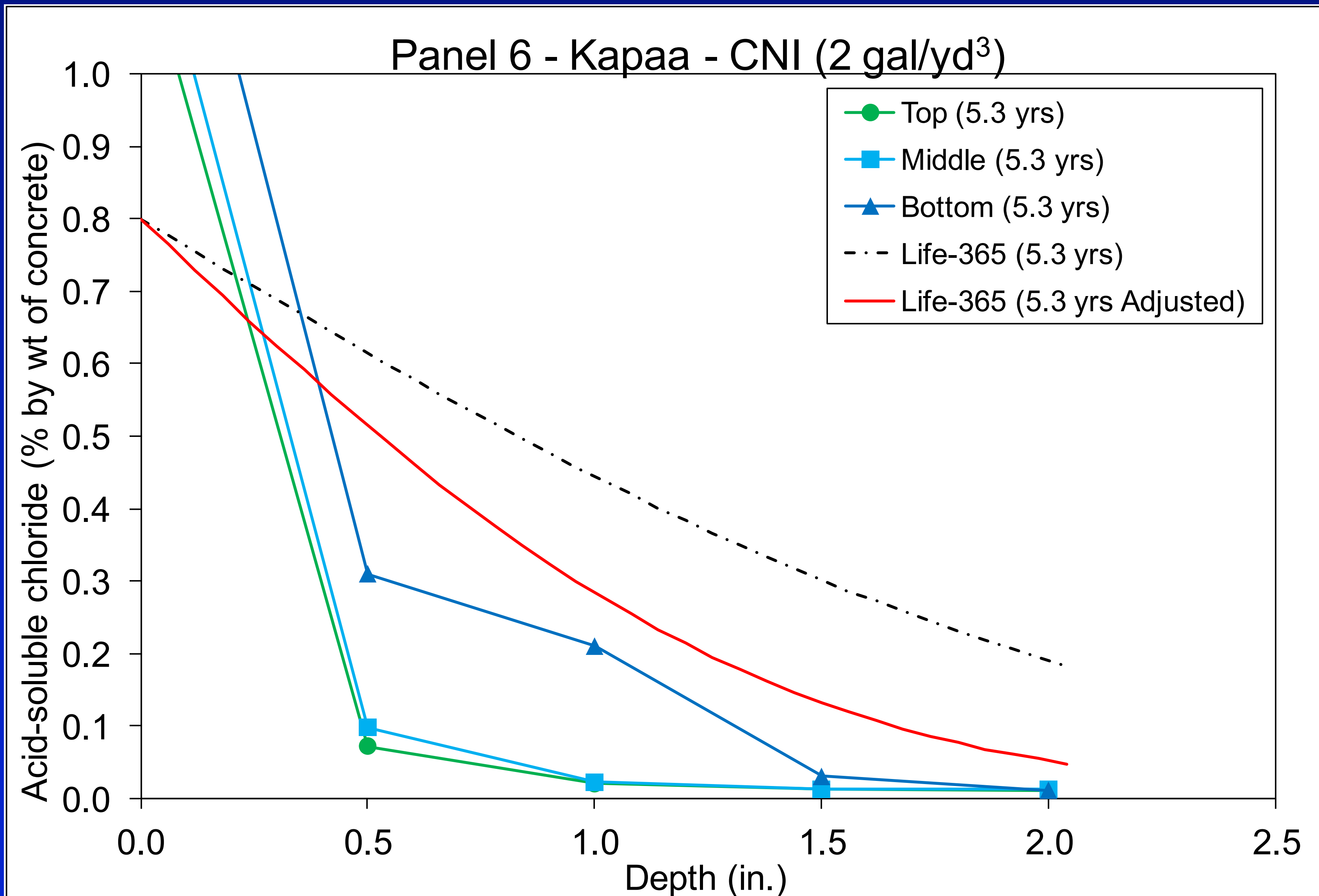
- Default and adjusted input values for CNI Panels

	Default values	Adjusted values
Diffusion coefficient	7.94E-12	5.50E-12
m	0.20	0.38
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions

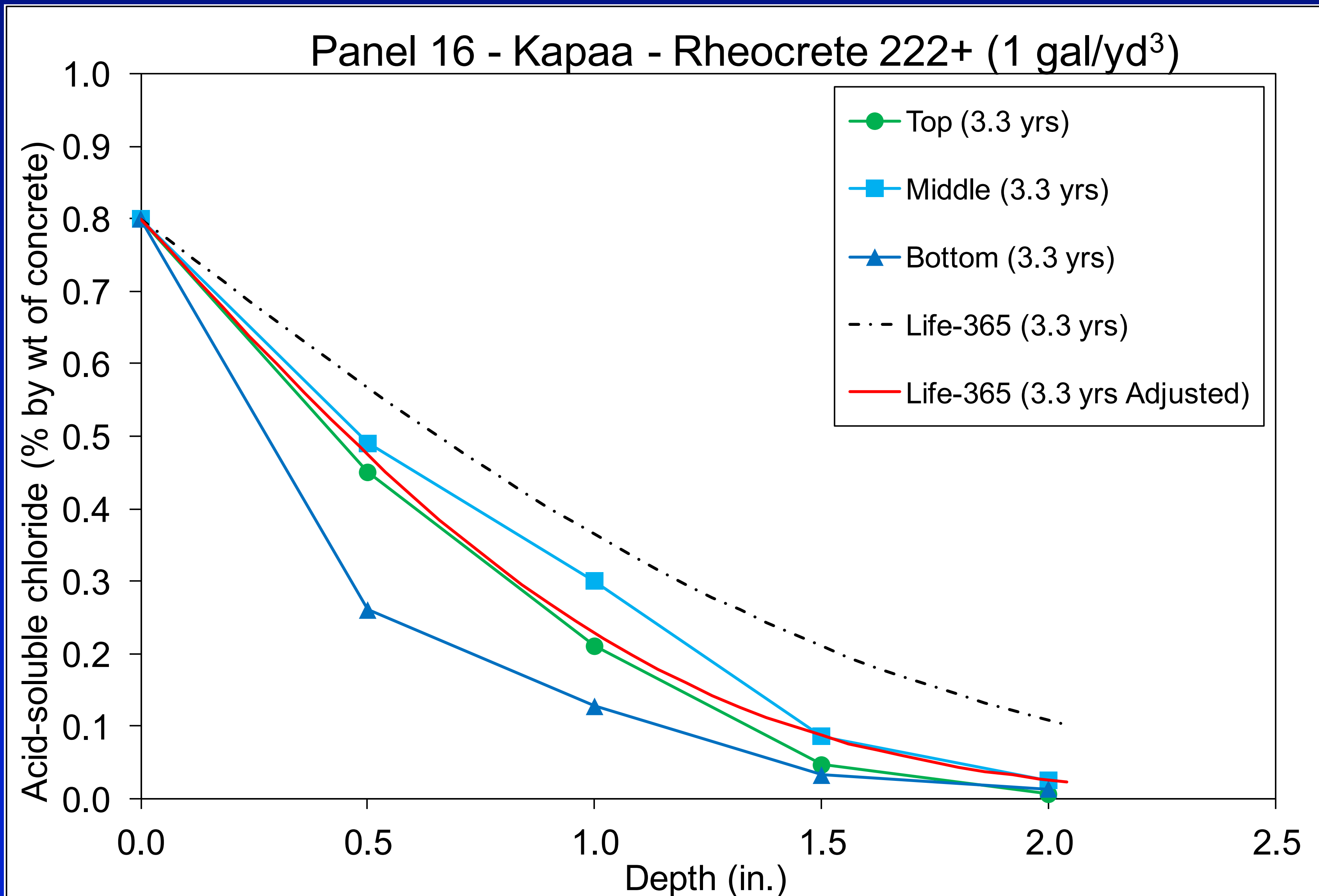


Chloride Concentrations with Life-365 Predictions

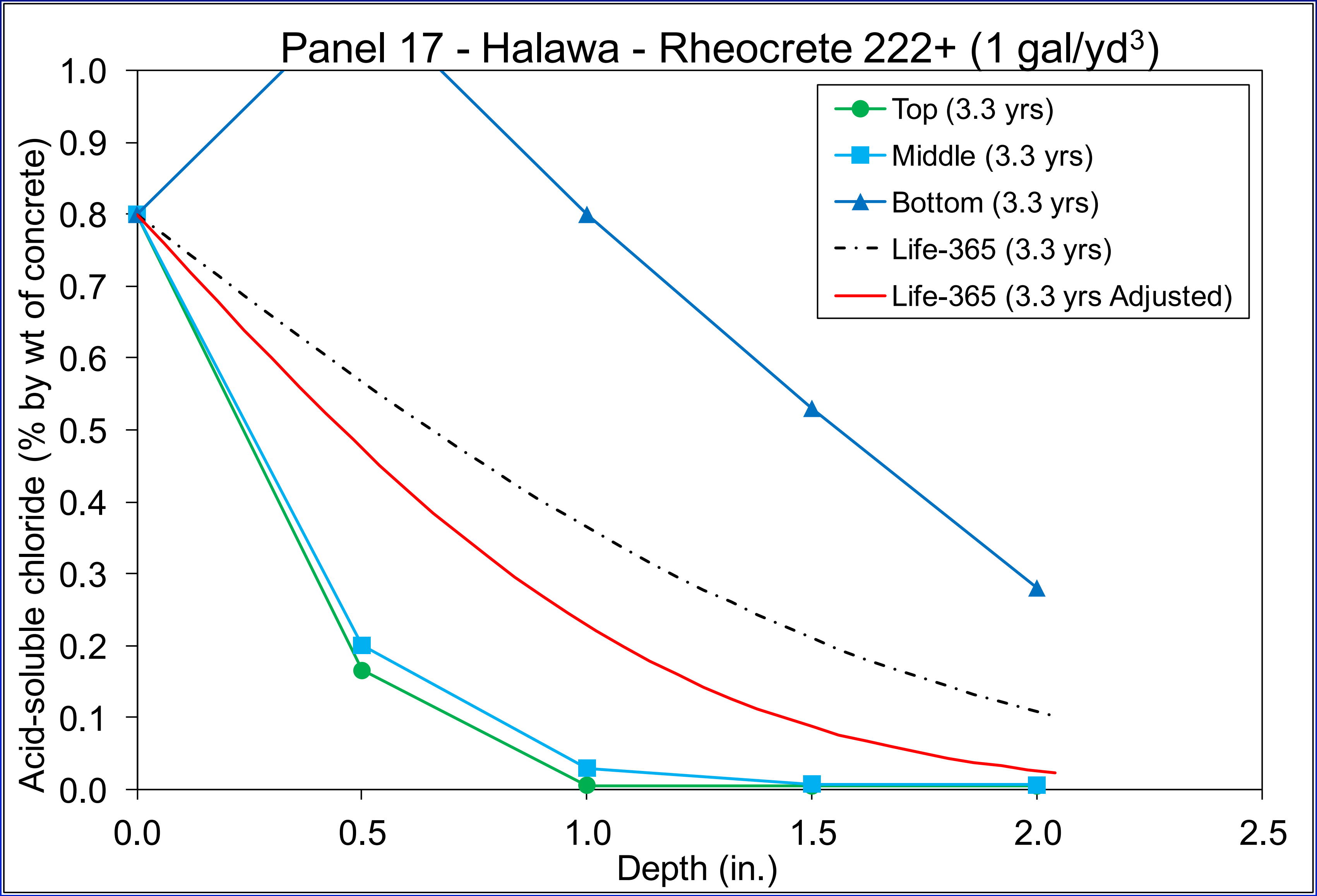
- Default and adjusted input values for Rheocrete 222+ Panels

	Default values	Adjusted values
Diffusion coefficient	7.94E-12	5.50E-12
m	0.20	0.38
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions

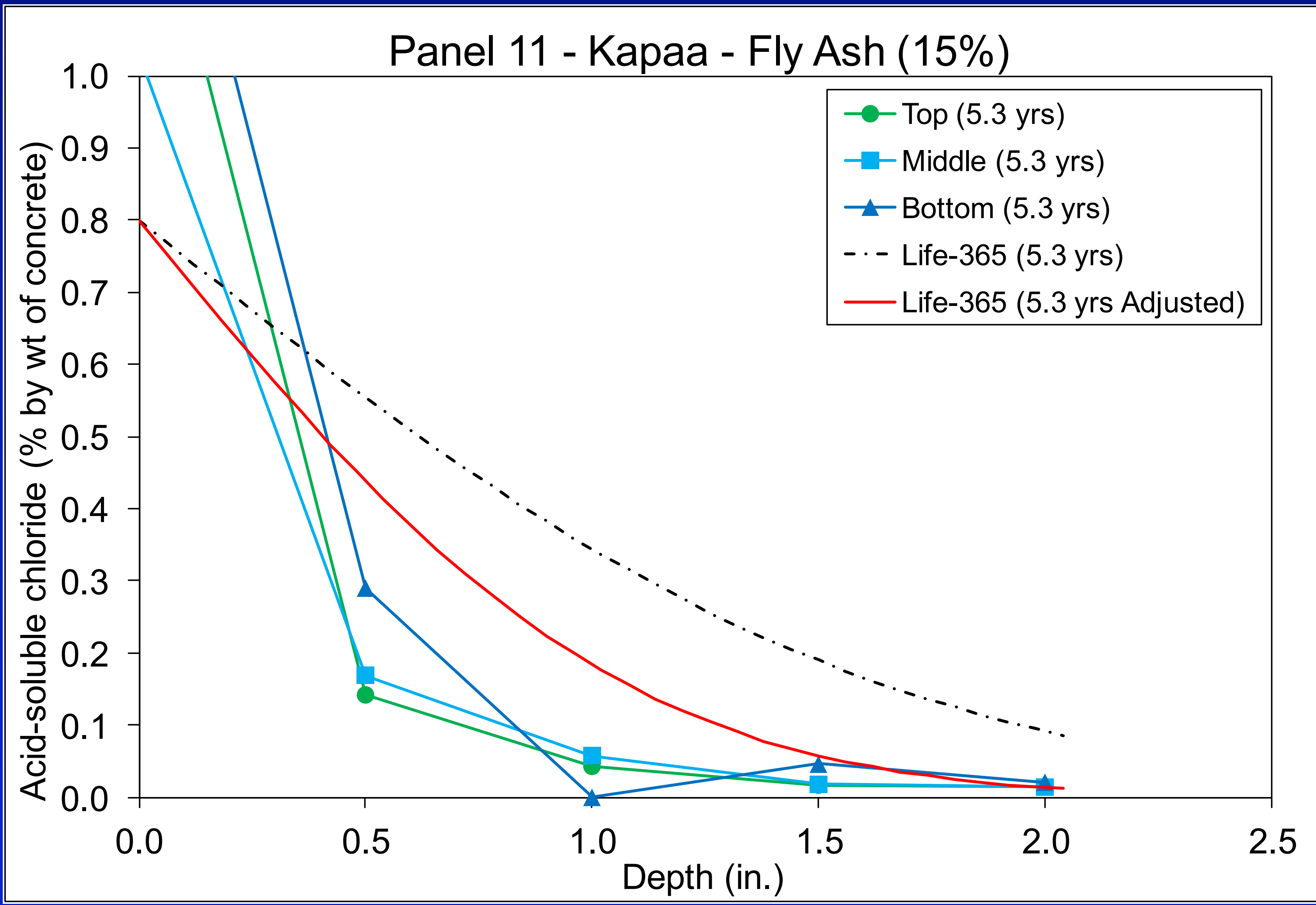


Chloride Concentrations with Life-365 Predictions

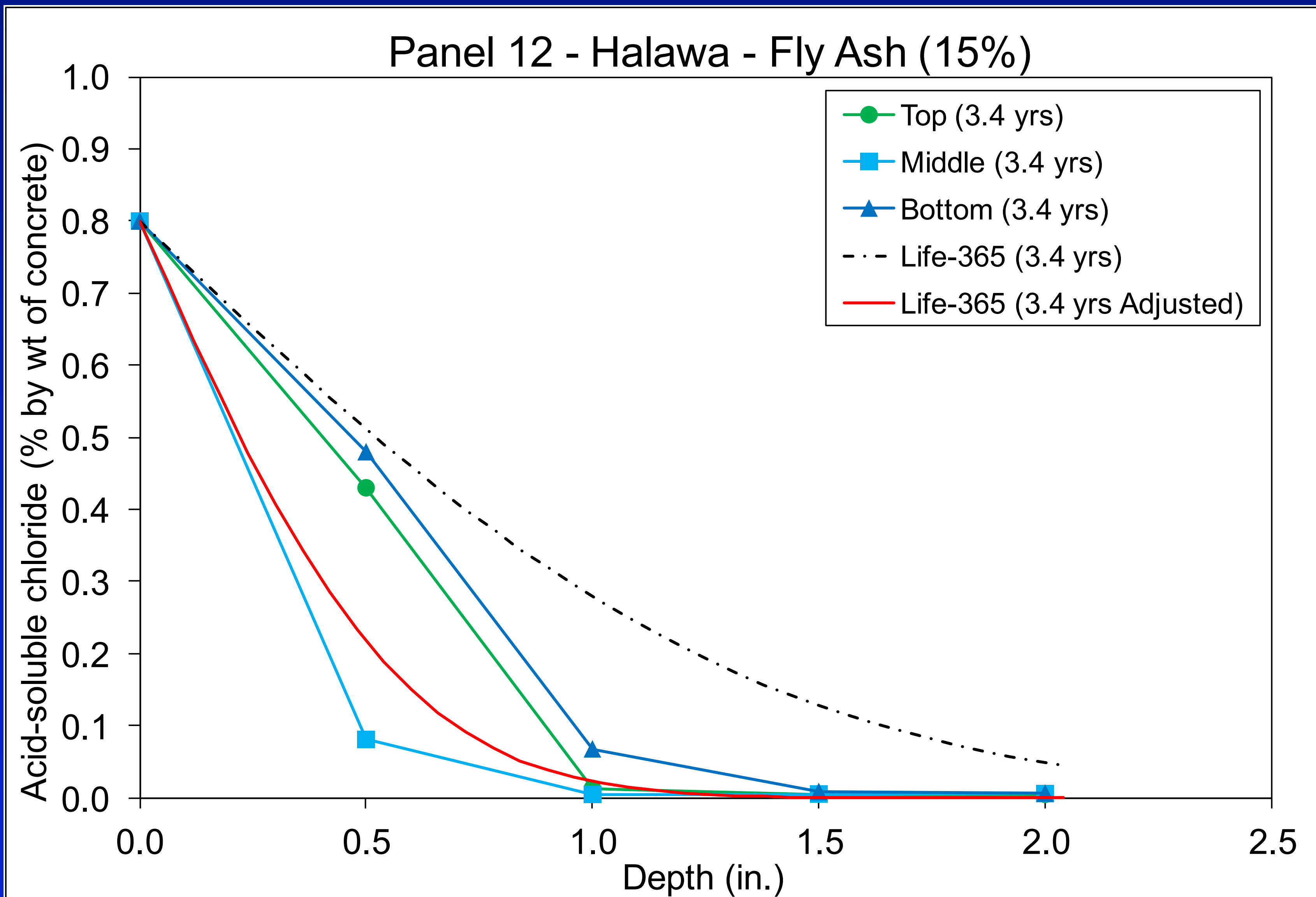
- Default and adjusted input values for Fly Ash Panels

	Default values	Adjusted values
Diffusion coefficient	6.37E-12	3.00E-12
m	0.32	0.35
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions

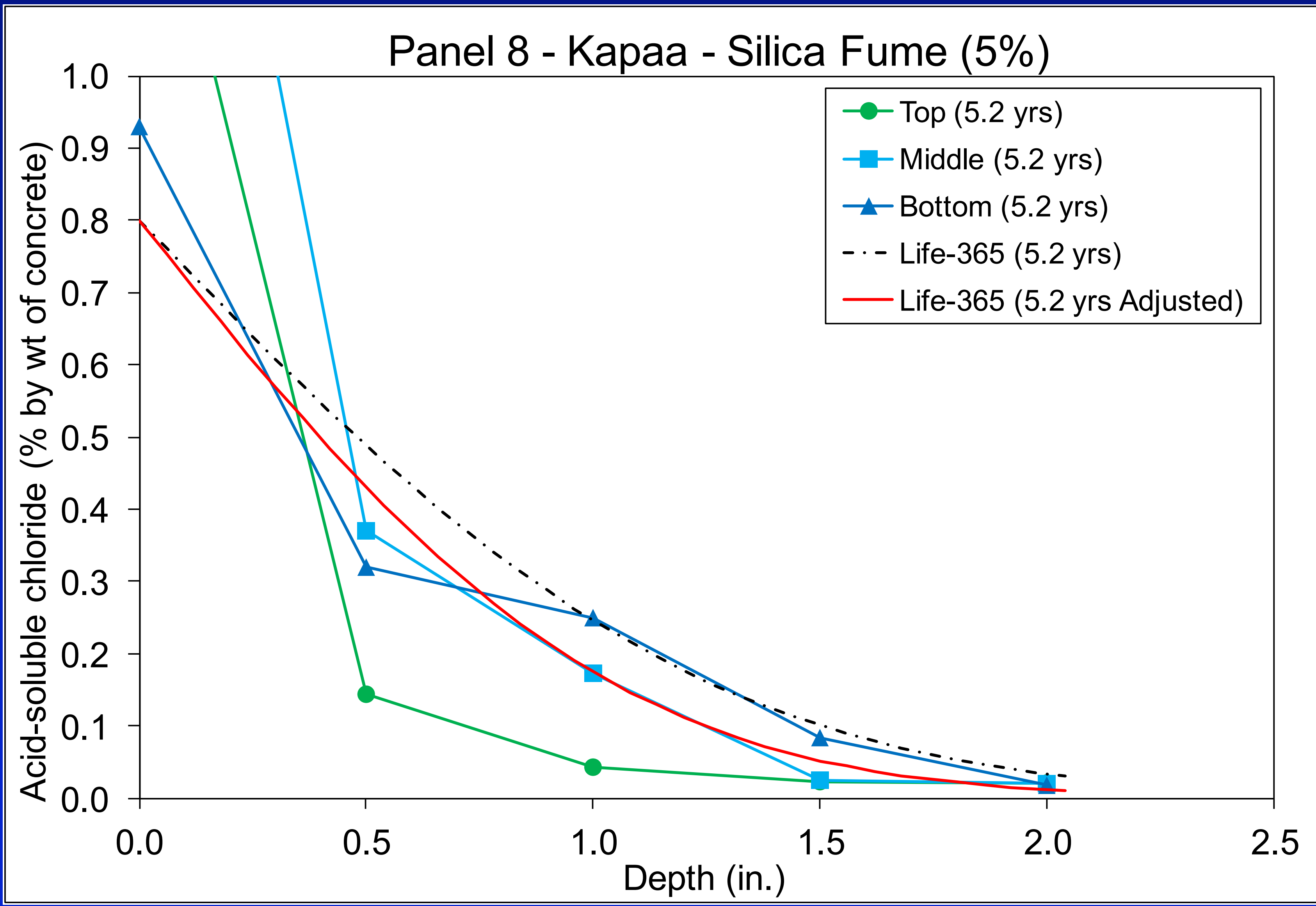


Chloride Concentrations with Life-365 Predictions

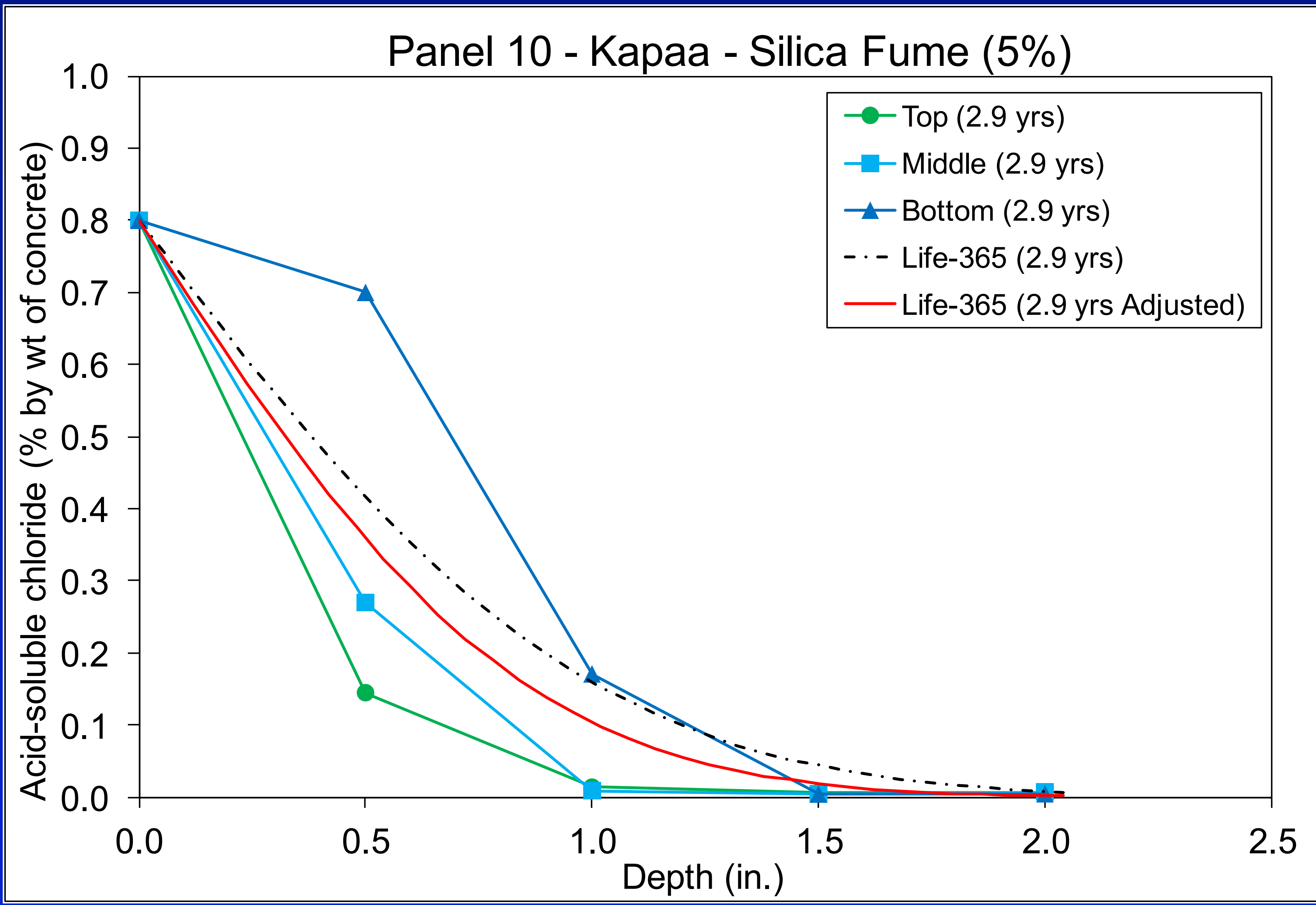
- Default and adjusted input values for Silica Fume Panels

	Default values	Adjusted values
Diffusion coefficient	2.71E-12	2.50E-12
m	0.20	0.30
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions



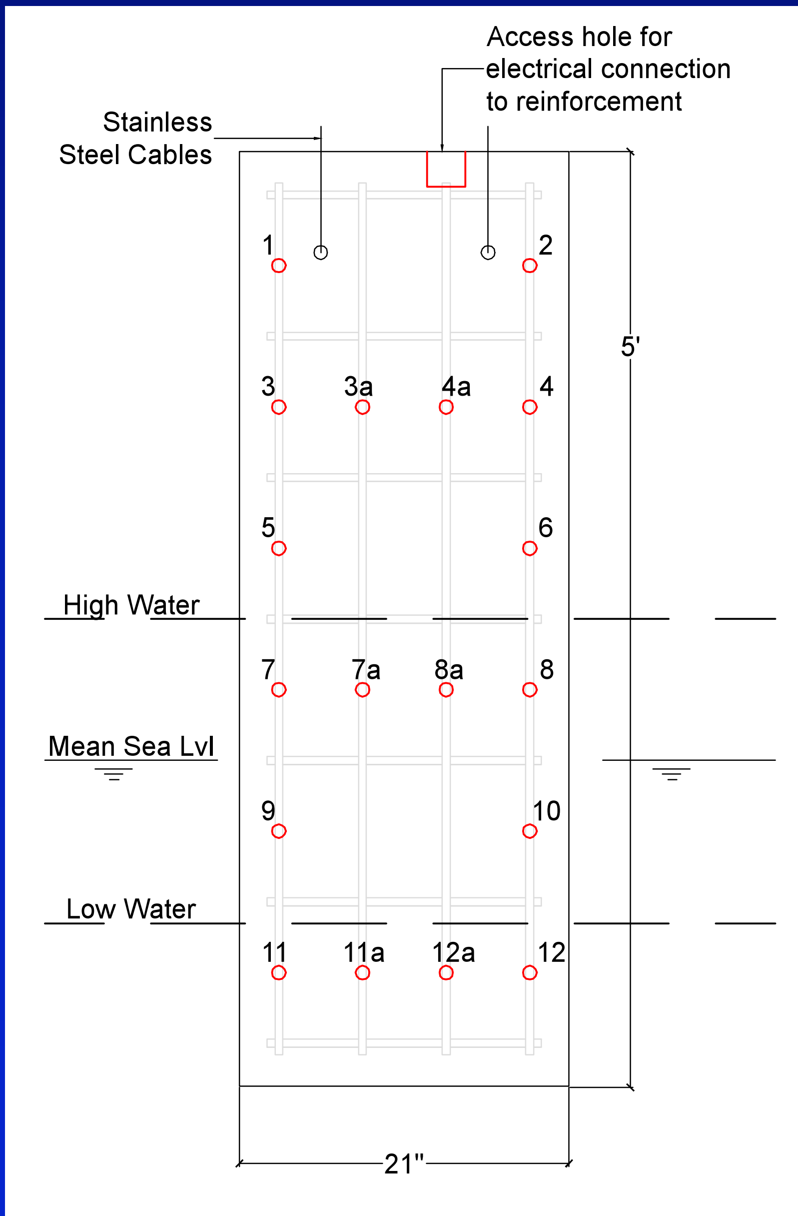
Half-cell Potential Tests

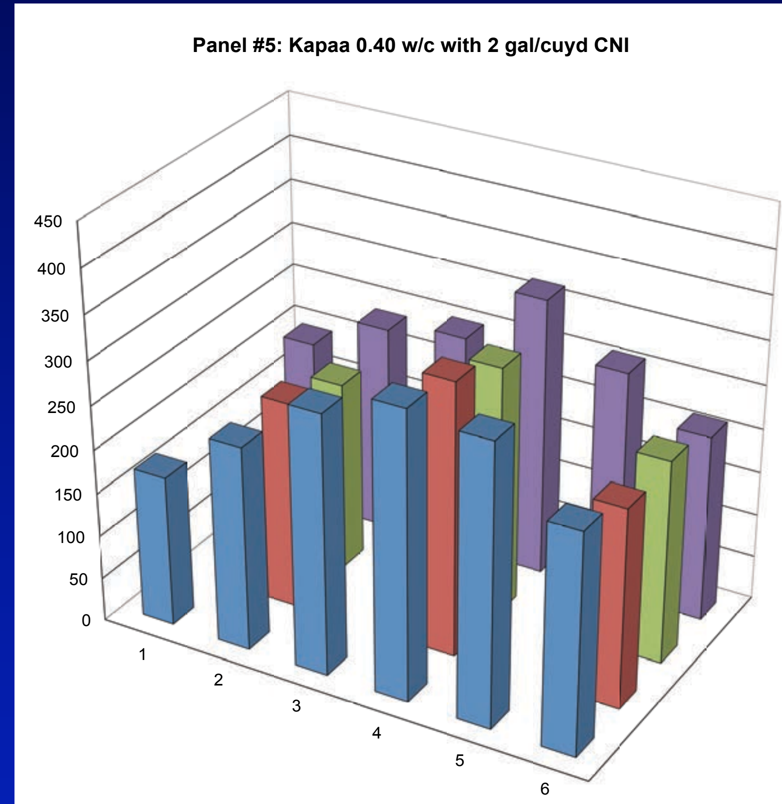
- Half-cell potential tests were performed to evaluate corrosion conditions within each field panel

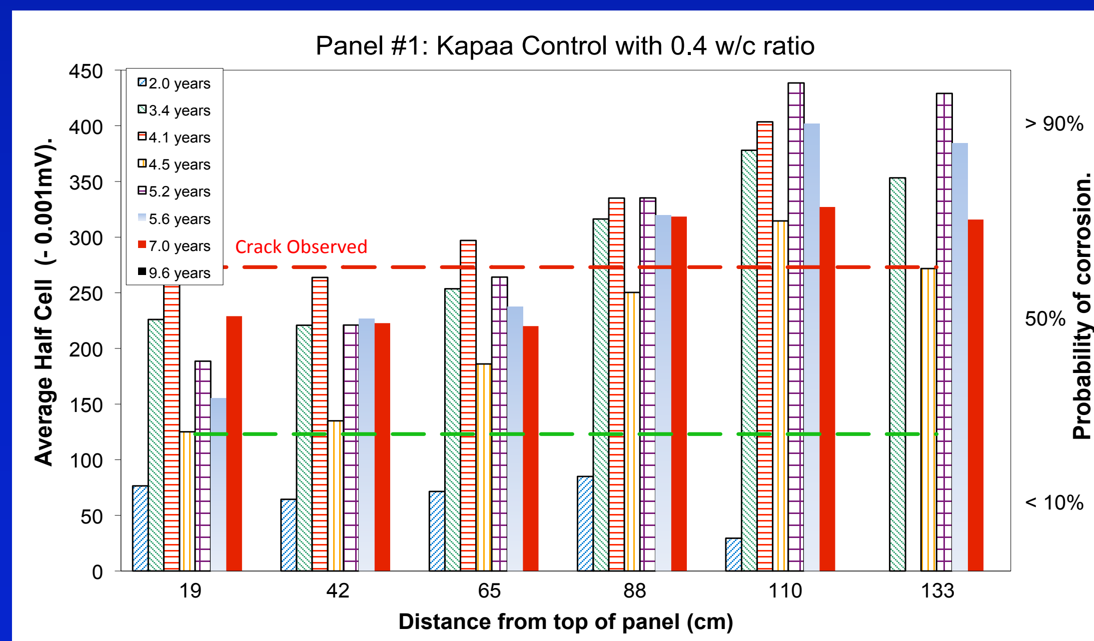
Measured Potential (mV)	Statistical risk of corrosion occurring
< -350	>90%
Between -350 and -200	50%
> -200	<10%

Reference electrode = Copper Sulfate Electrode (CSE)

Testing
Half-cell Potential

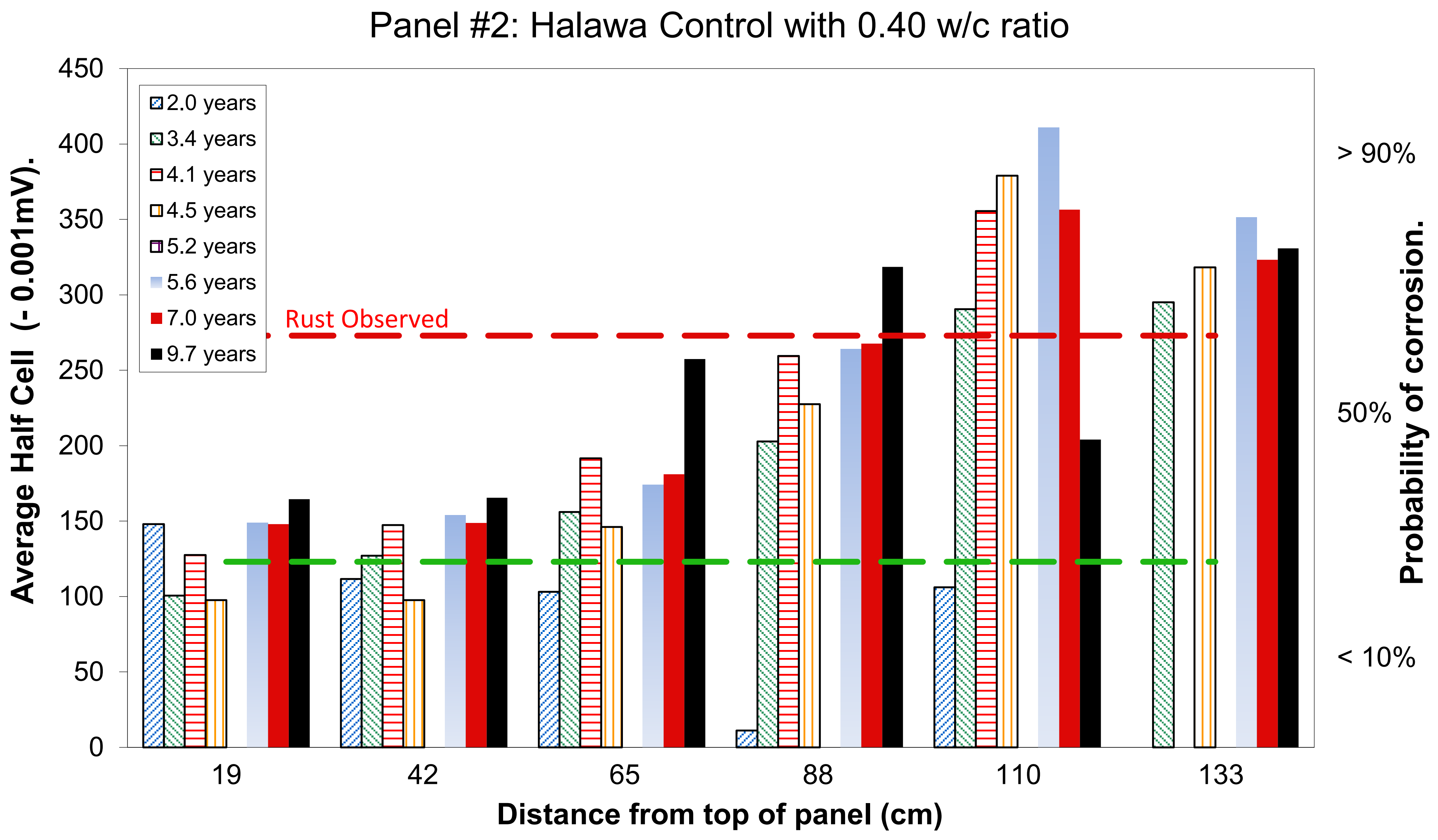






Final Autopsy of Field Panels

Panel 2: Halawa Control with 0.40 w/c ratio



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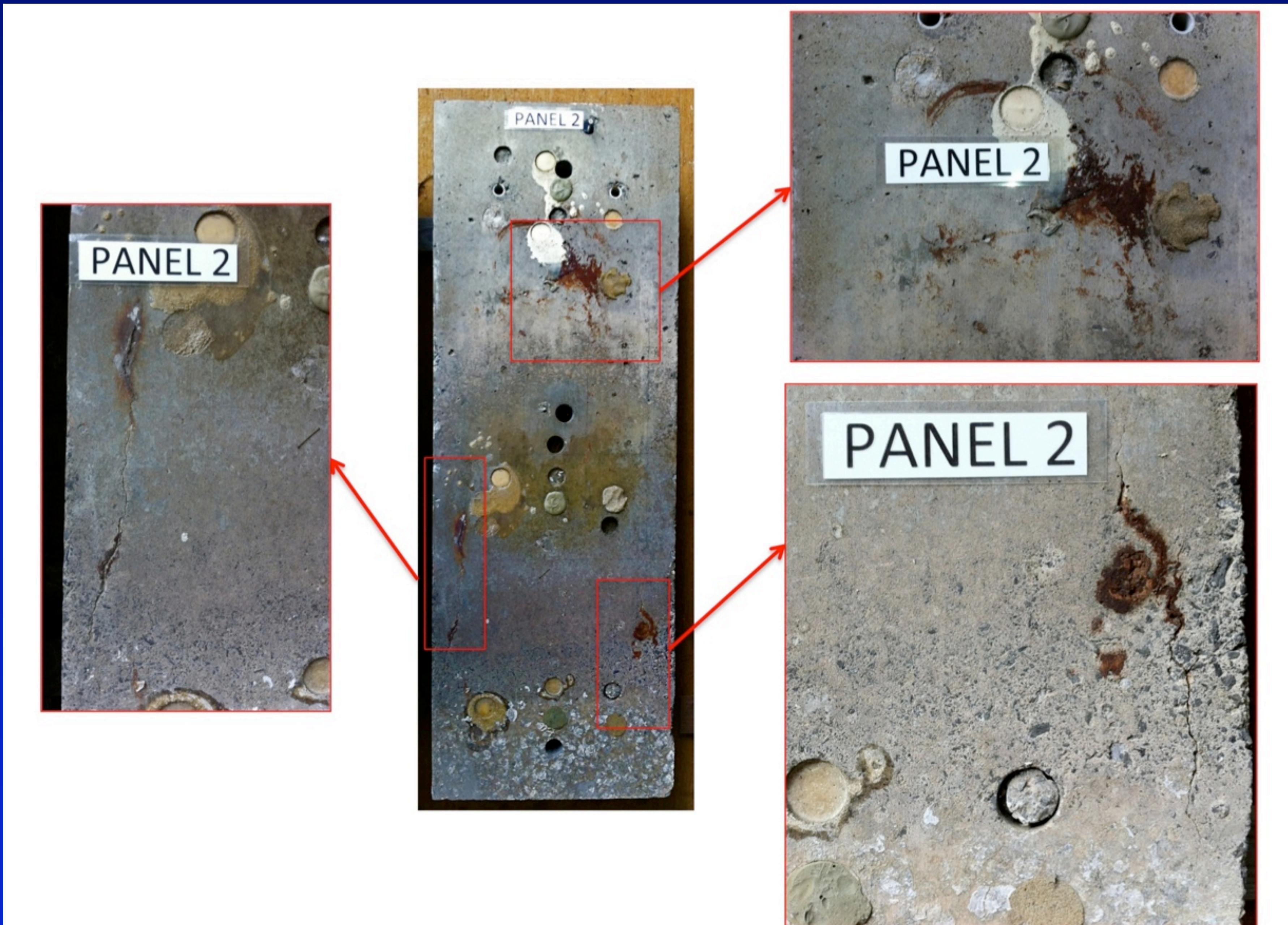

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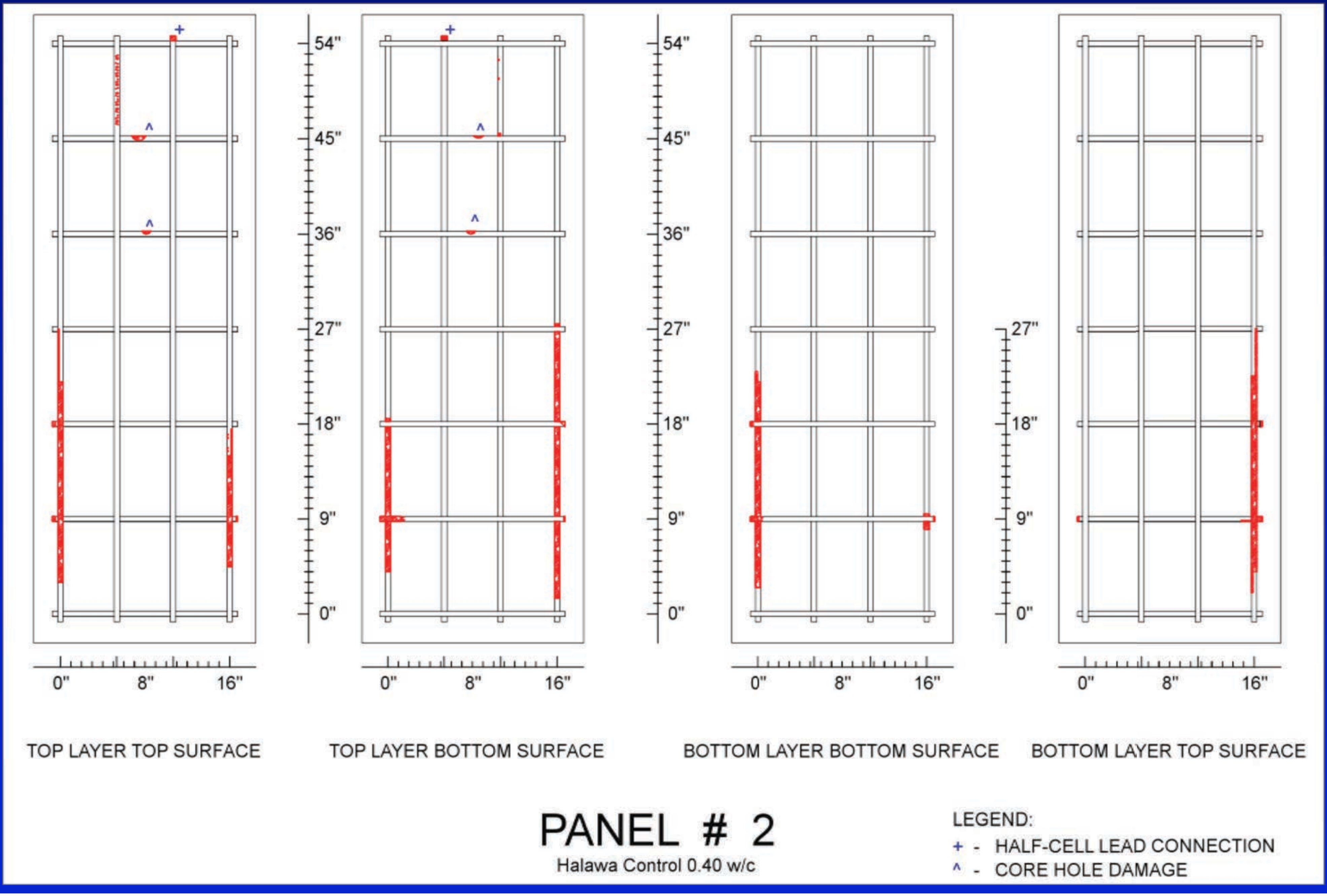

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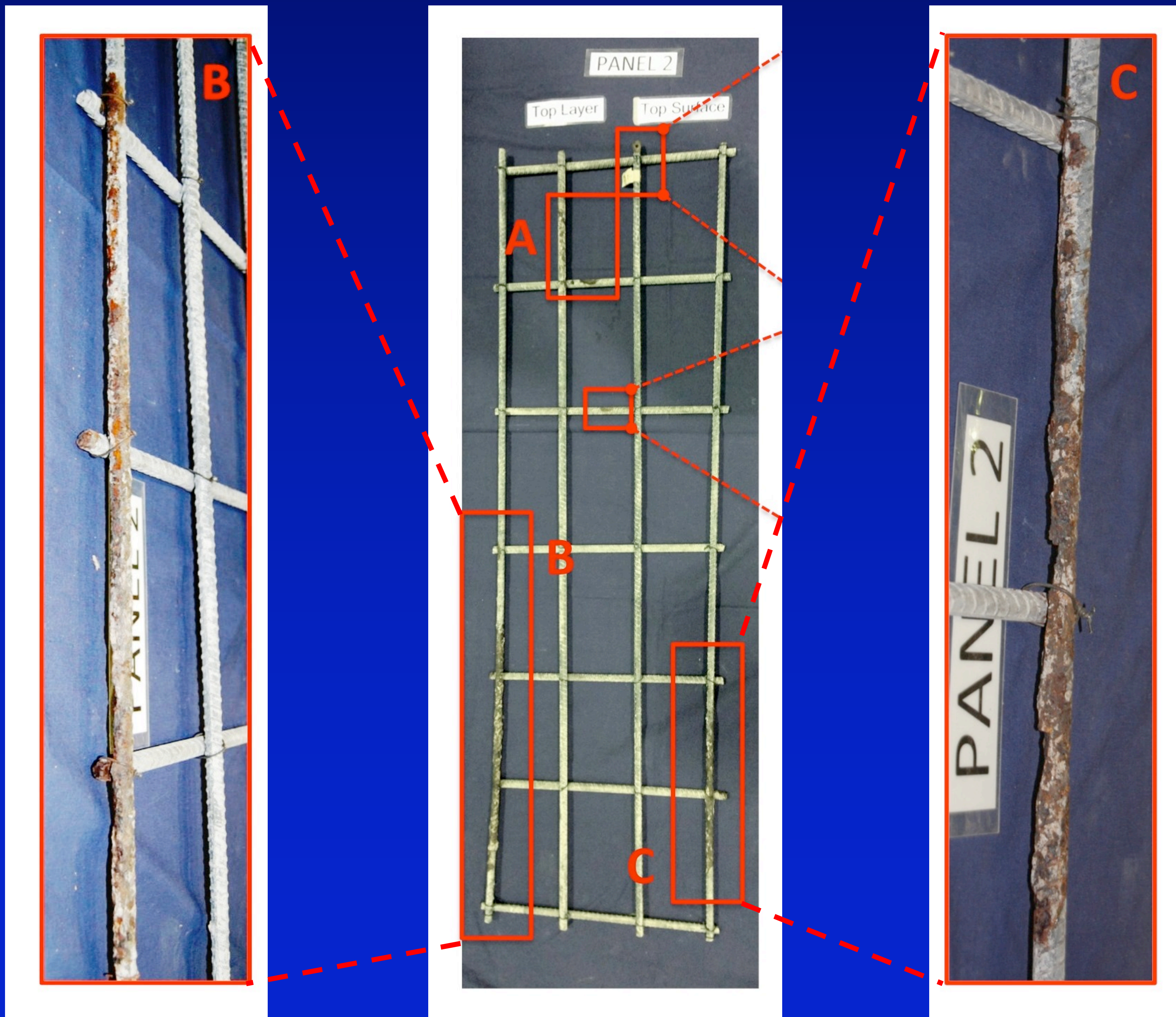
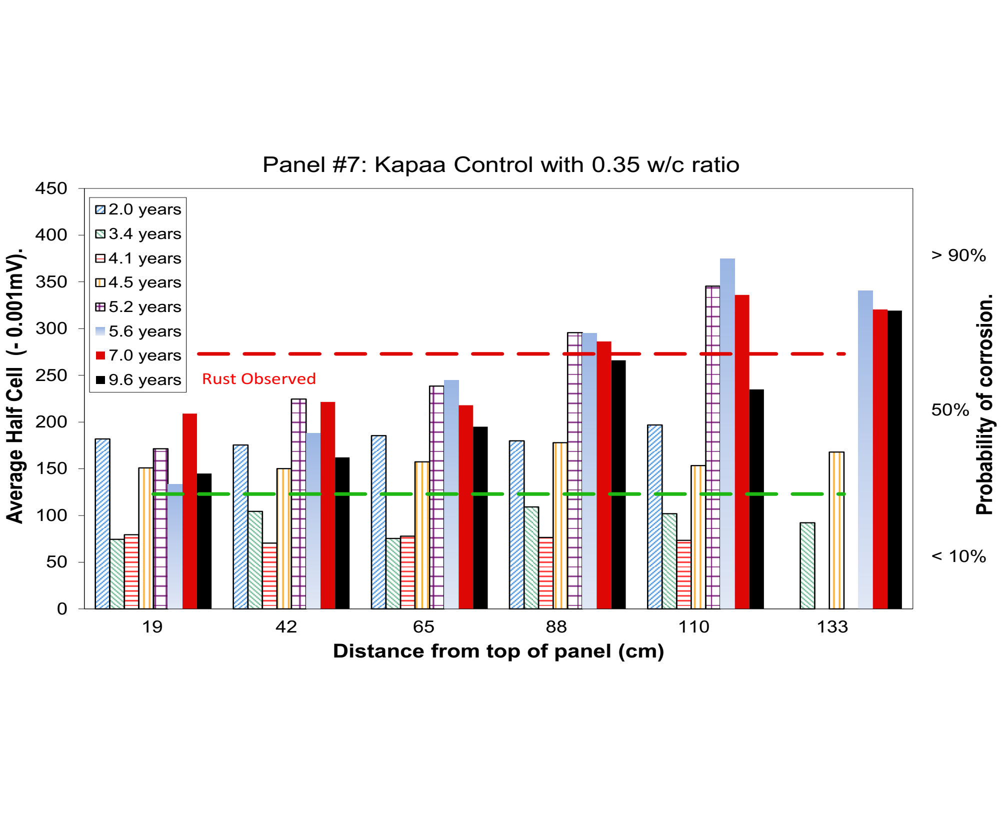
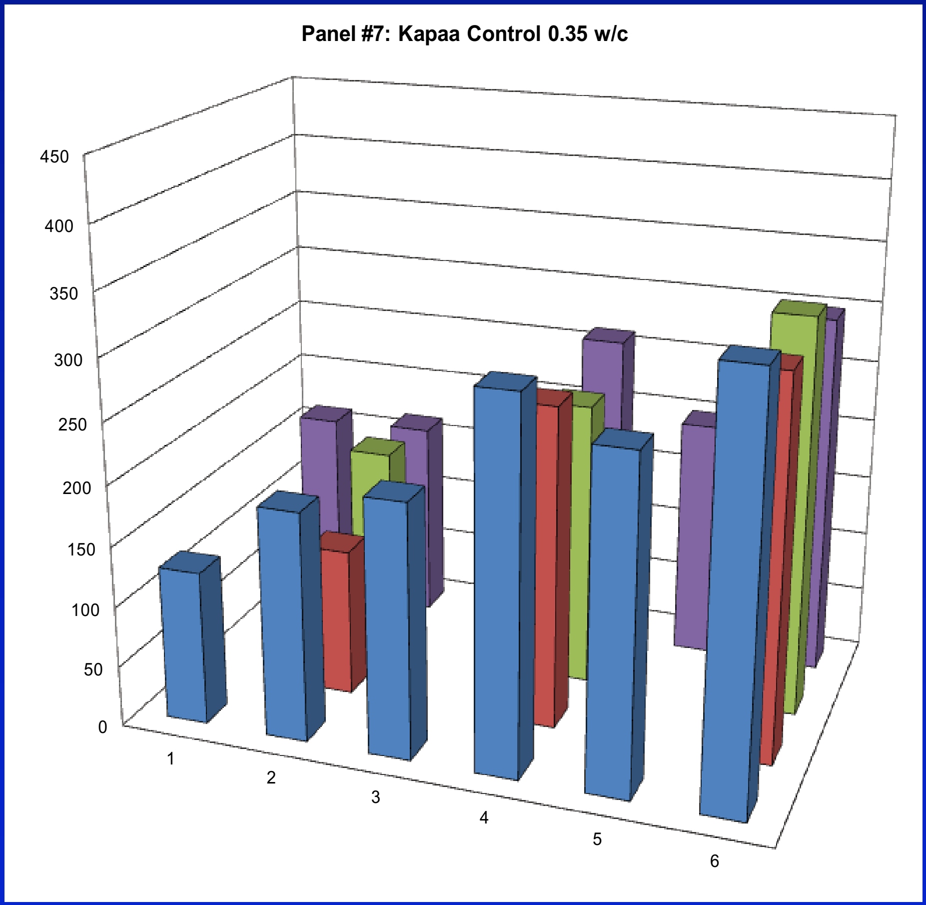


Panel 7: Kapaa Control - 0.35 w/cm

Half-Cell Potential at Various Years



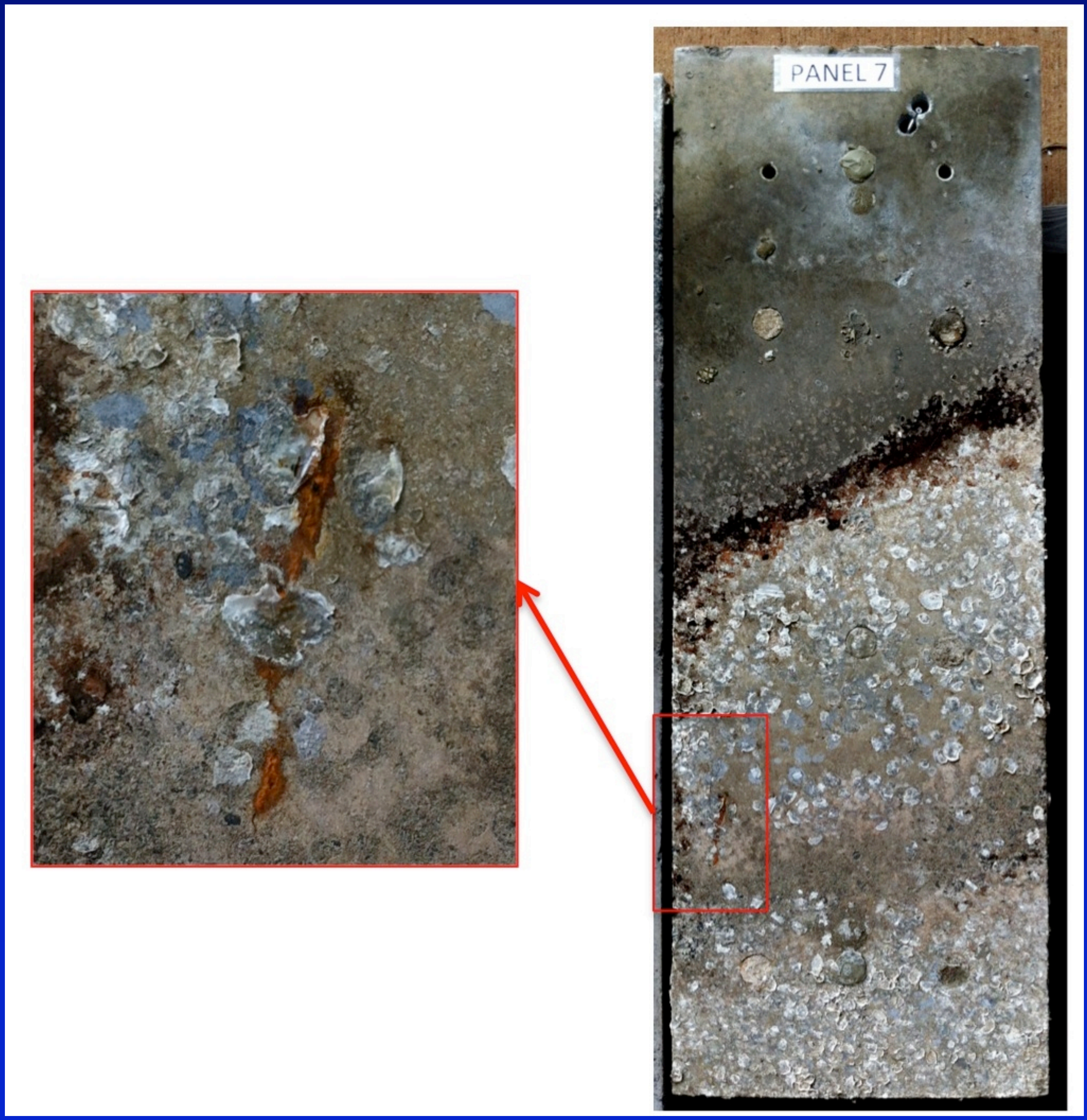
Half-Cell potential at 9.6 years



Panel 7: Kapaa Control - 0.35 w/cm

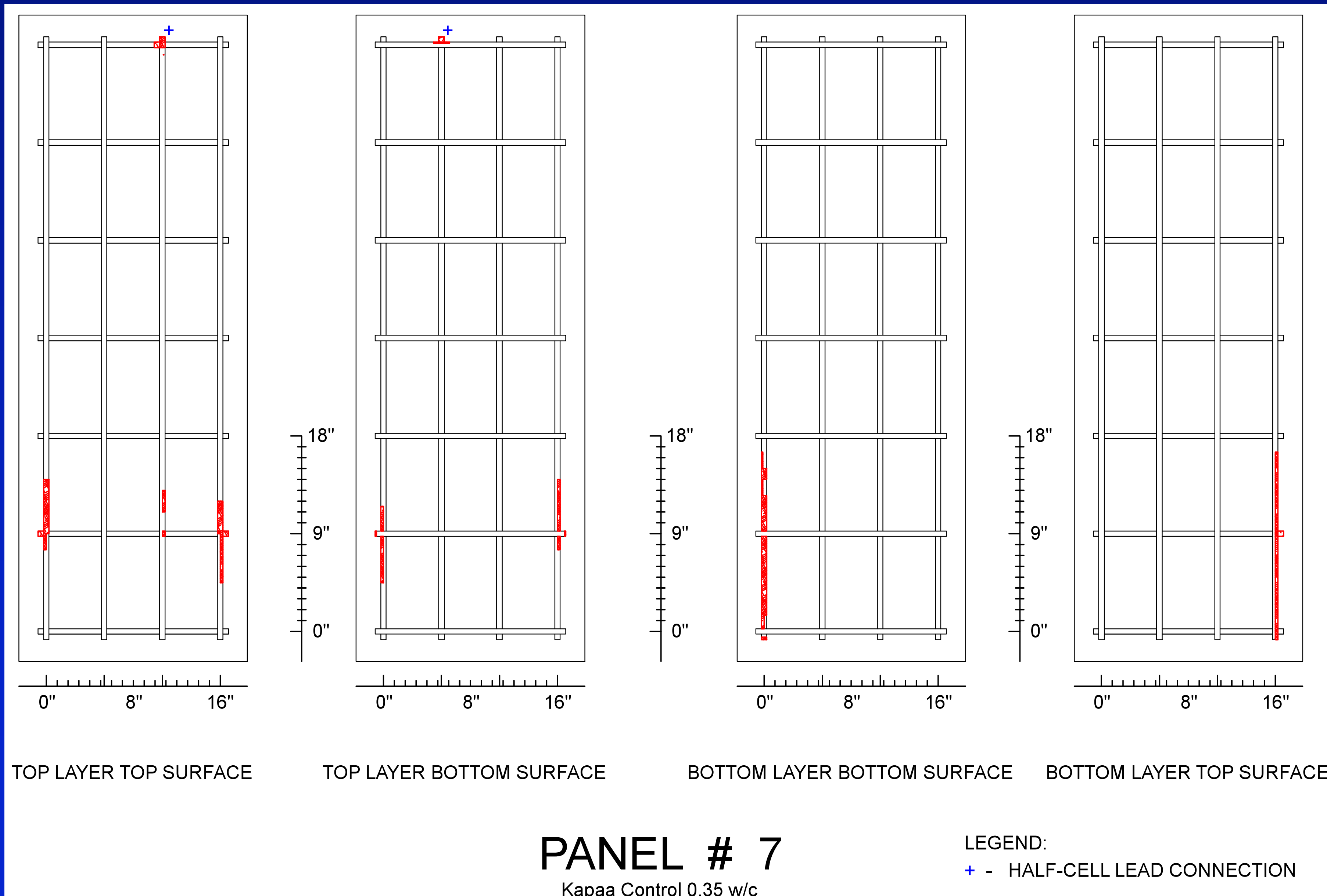
Visual Observation

Rust on Front Edge

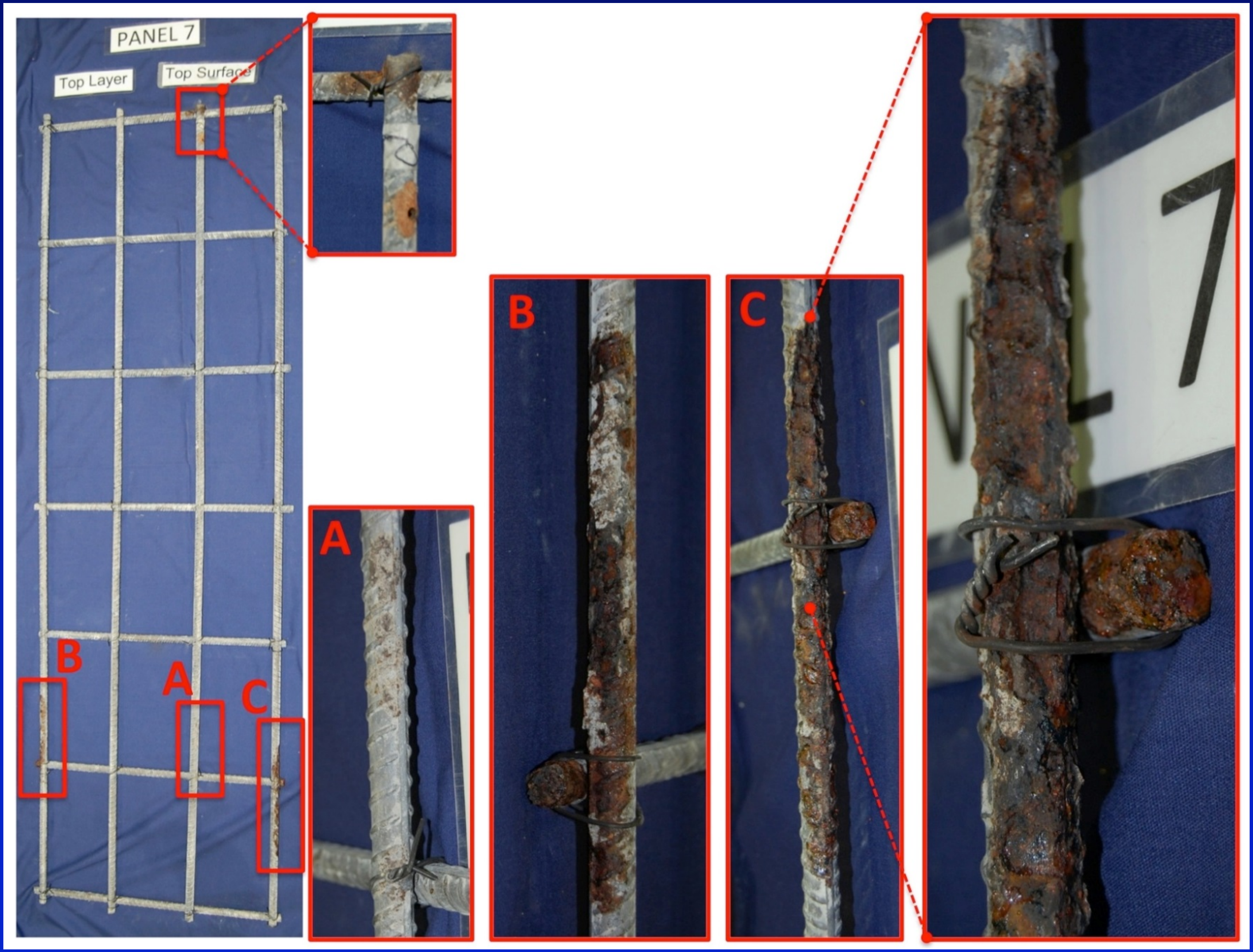


Panel 7: Kapaa Control - 0.35 w/cm

Visual Observation – Reinforcing Steel



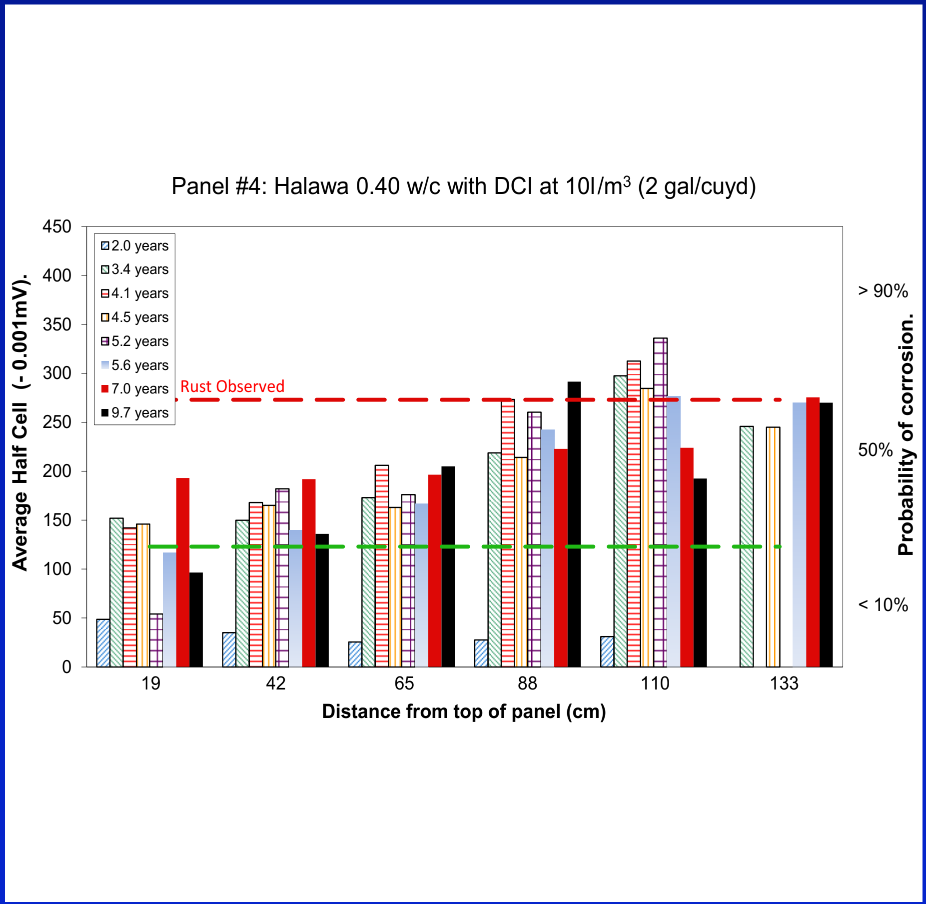
Panel 7: Kapaa Control - 0.35 w/cm



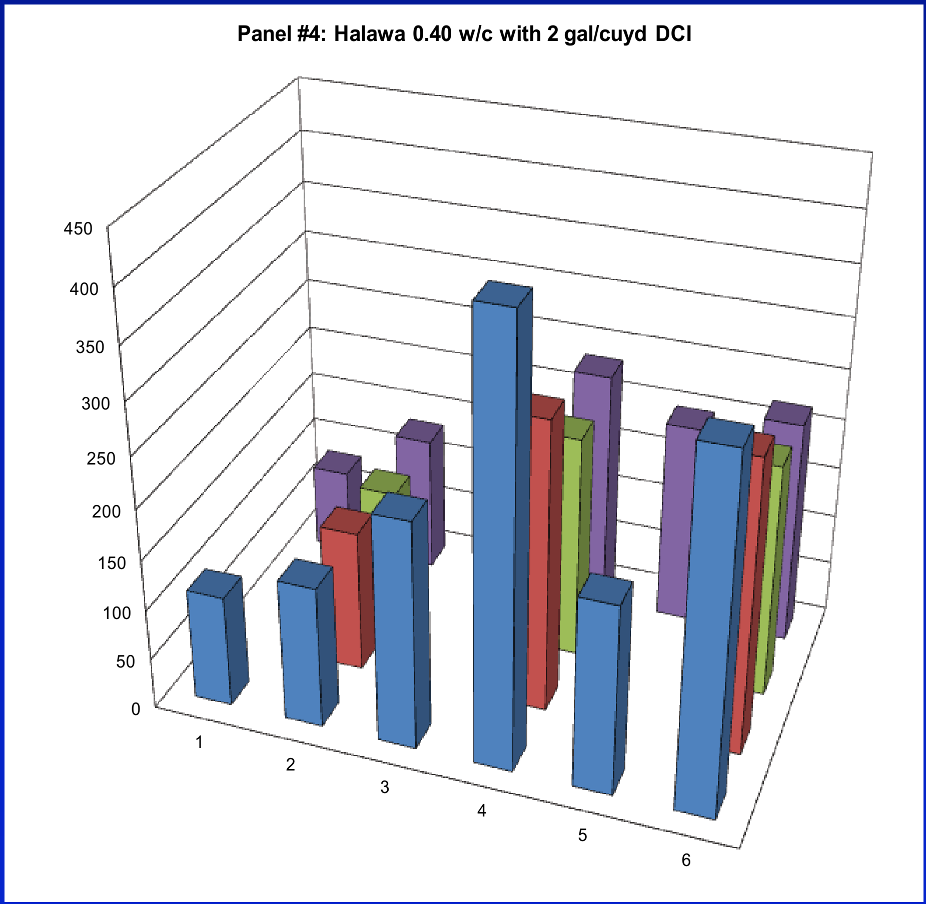
Visual Observation of Panel 7 Top Layer Top Surface Reinforcing Steel

Panel 4: Halawa 0.40 w/cm with 10 *l*/m^3 DCI

Half-Cell Potential Various Years



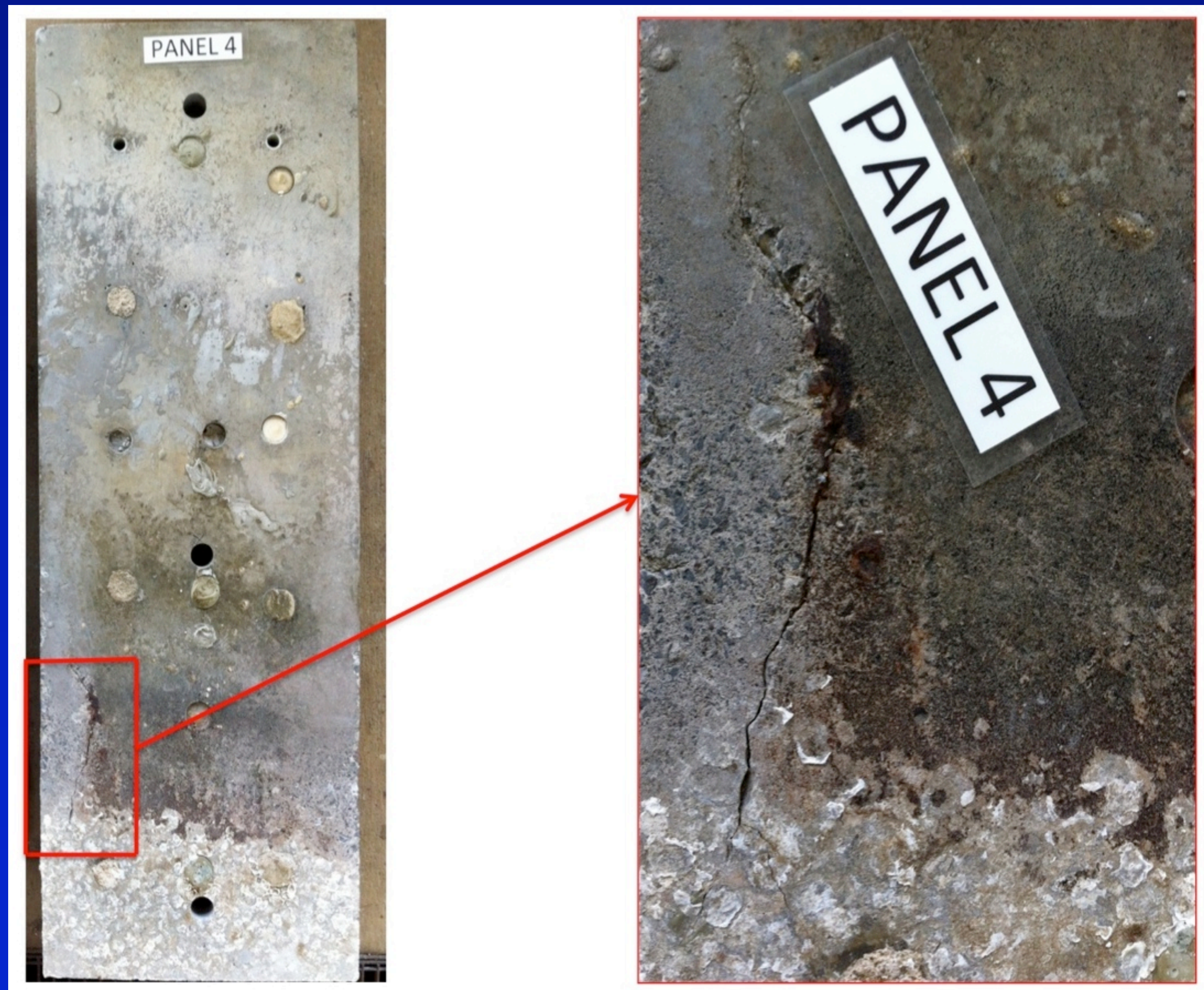
Half-Cell potential at 9.7 years



Panel 4: Halawa 0.40 w/cm with 10 l/m^3 DCI

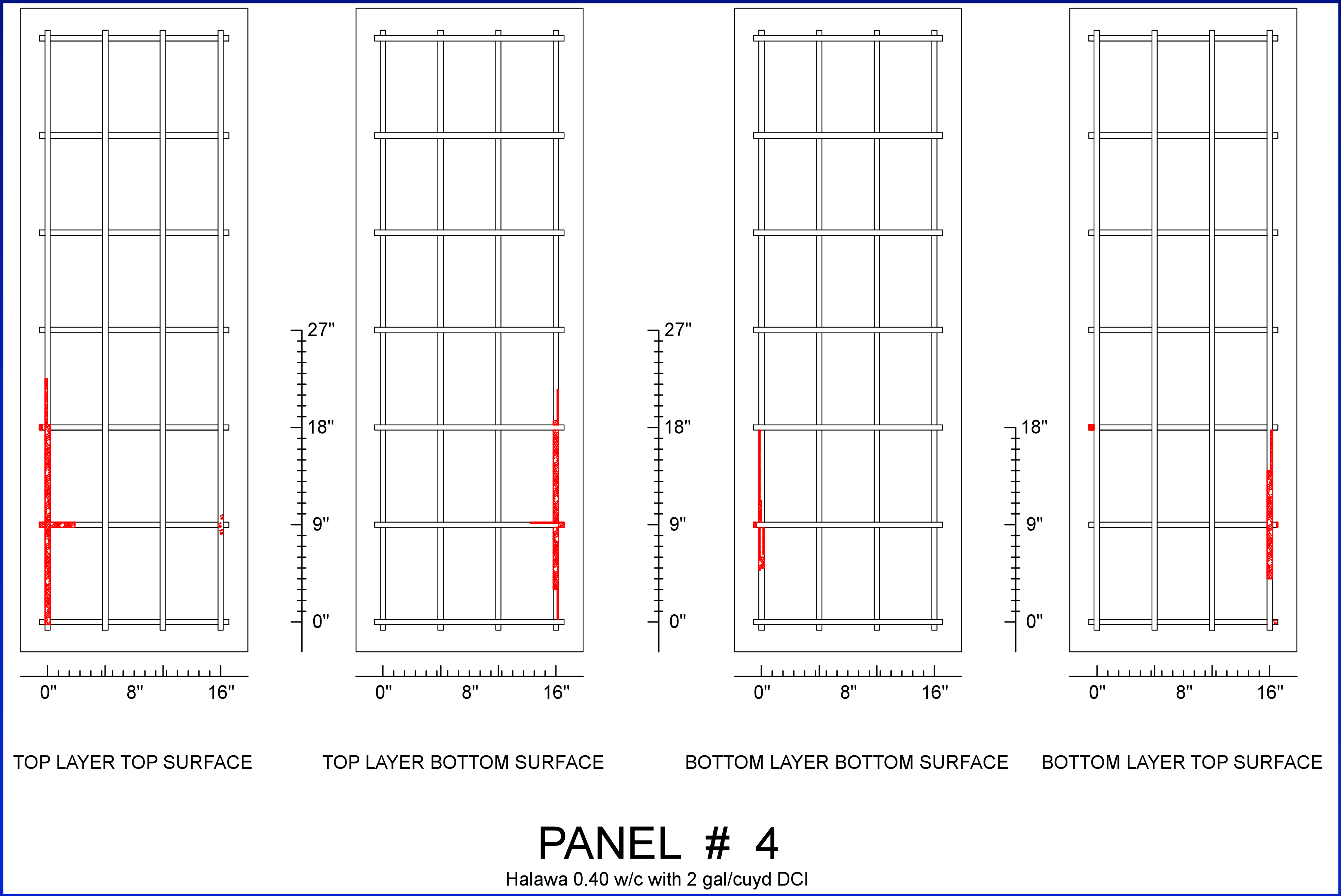
Visual Observation

Crack and Rust at Front edge of Panel 4

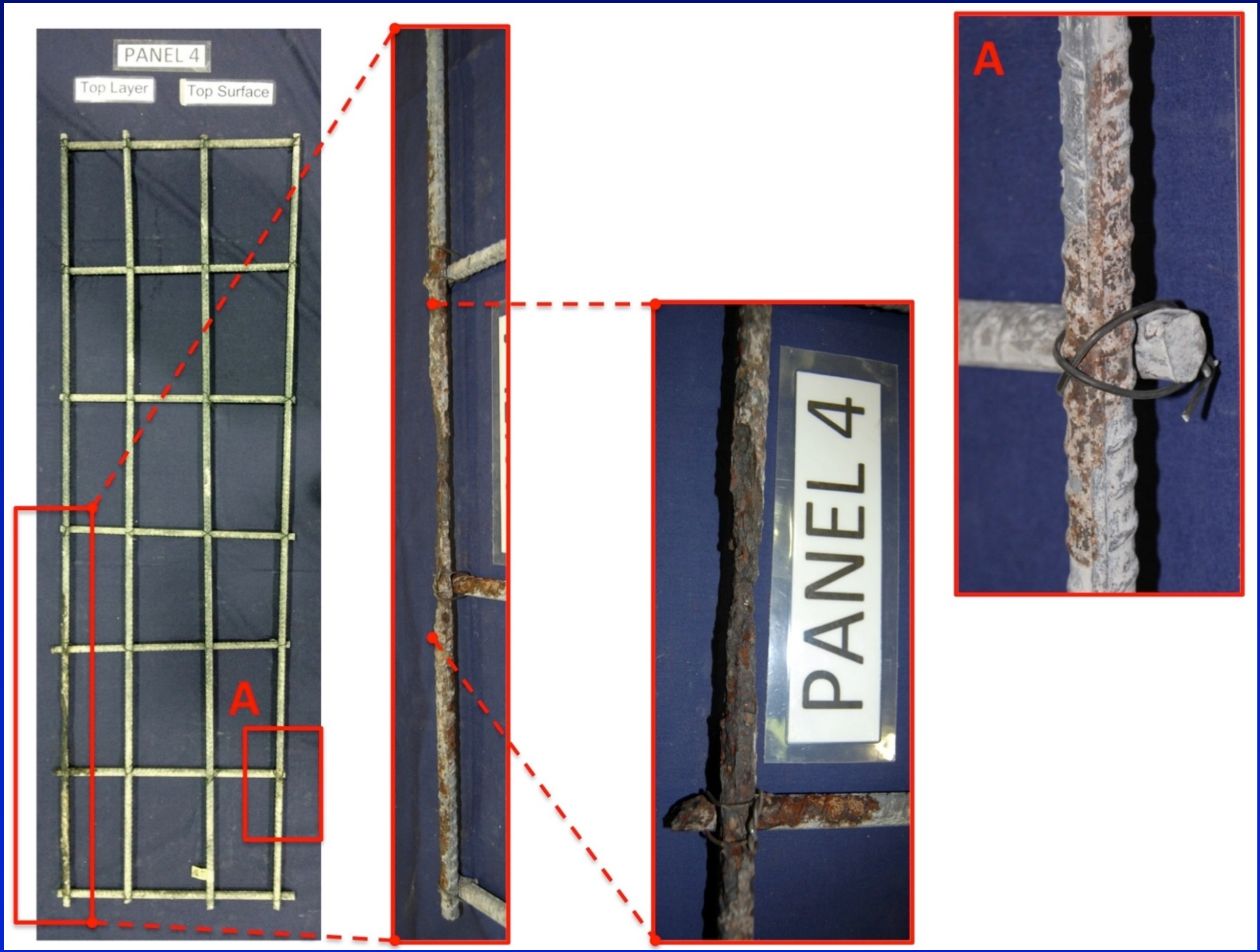


Panel 4: Halawa 0.40 w/cm with 10 *l*/m^3 DCI

Visual Observation – Reinforcing Steel

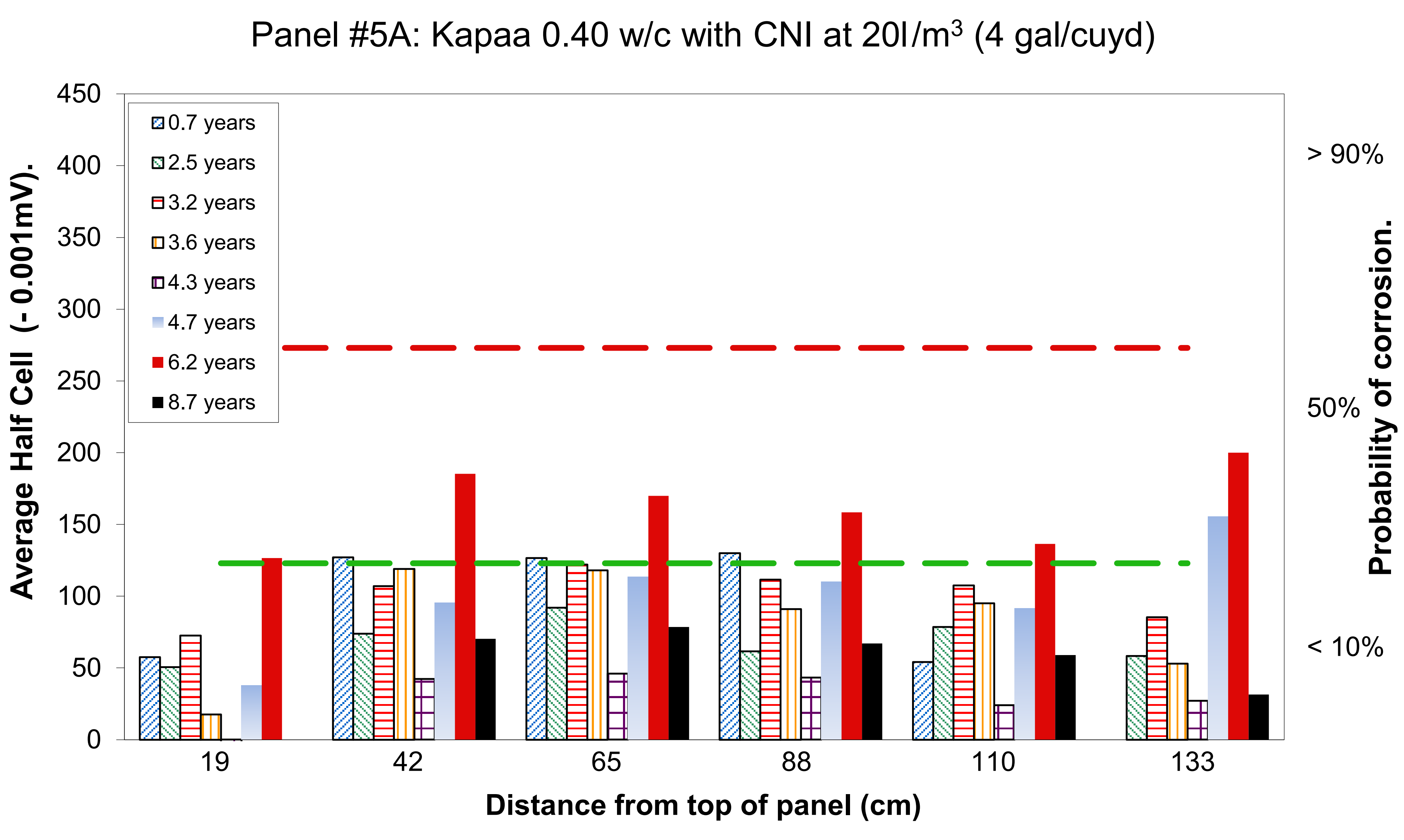


Panel 4: Halawa 0.40 w/cm with 10 l/m^3 DCI

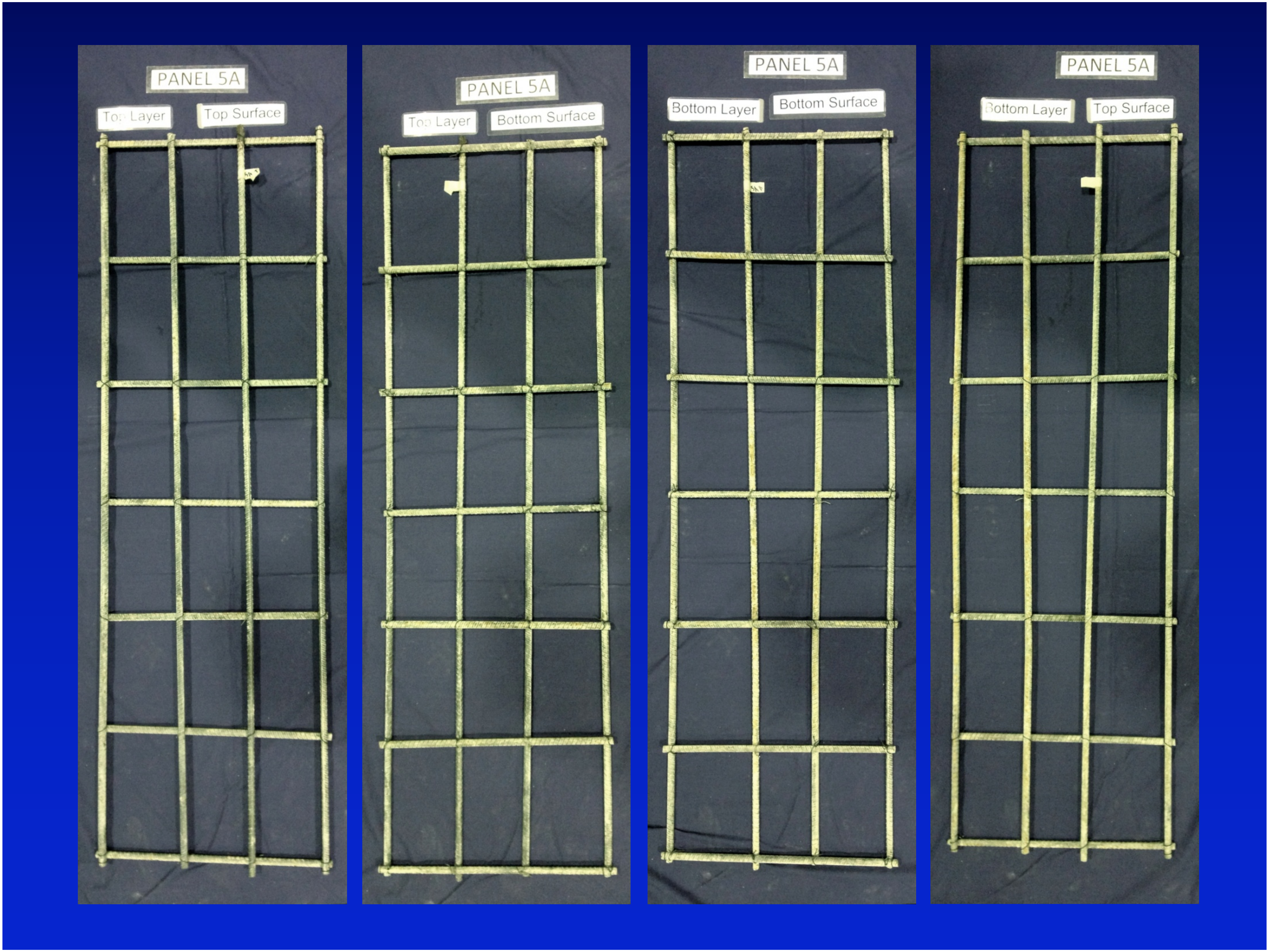


Visual Observation of Panel 4 Top Layer Top Surface Reinforcing Steel

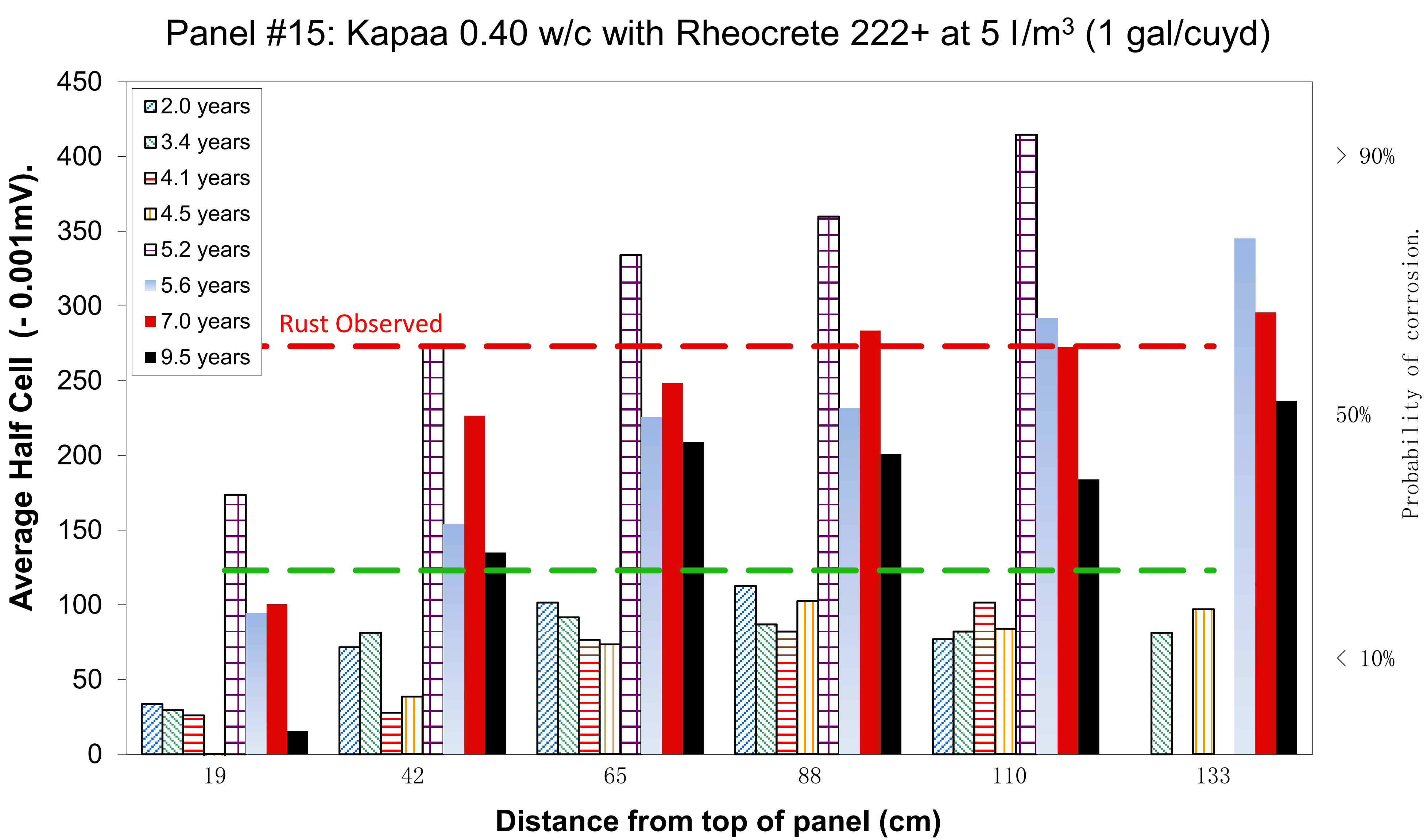
Panel 5A: Kapaa 0.40 w/c ratio w/ 20 *l*/m³ CNI



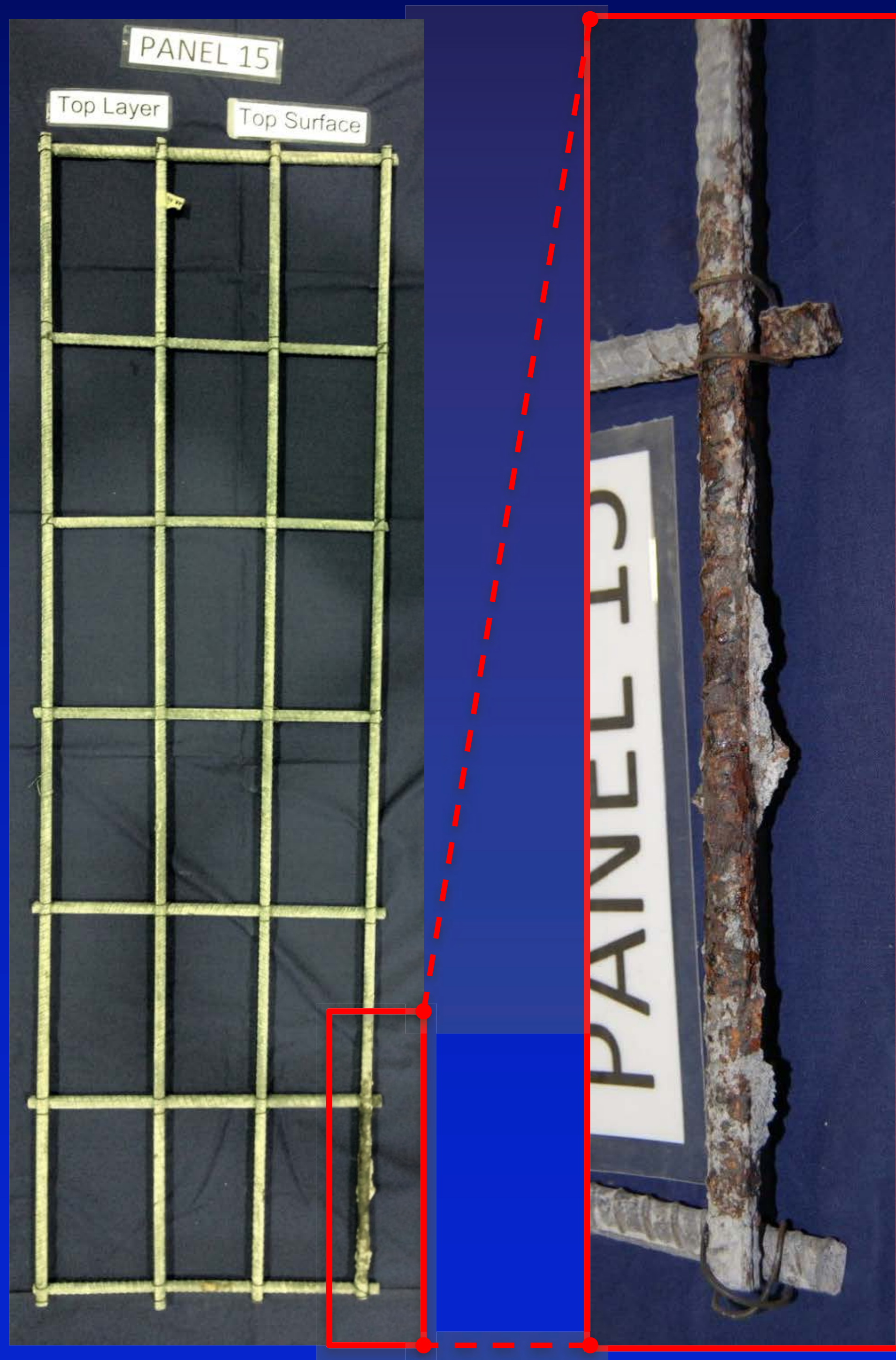
Panel 5A: Kapaa 0.40 w/c ratio w/ 20 l/m^3 CNI


PANEL 5A
Top Layer
Top Surface
PANEL 5A
Top Layer
Bottom Surface
PANEL 5A
Bottom Layer
Bottom Surface
PANEL 5A
Bottom Layer
Top Surface

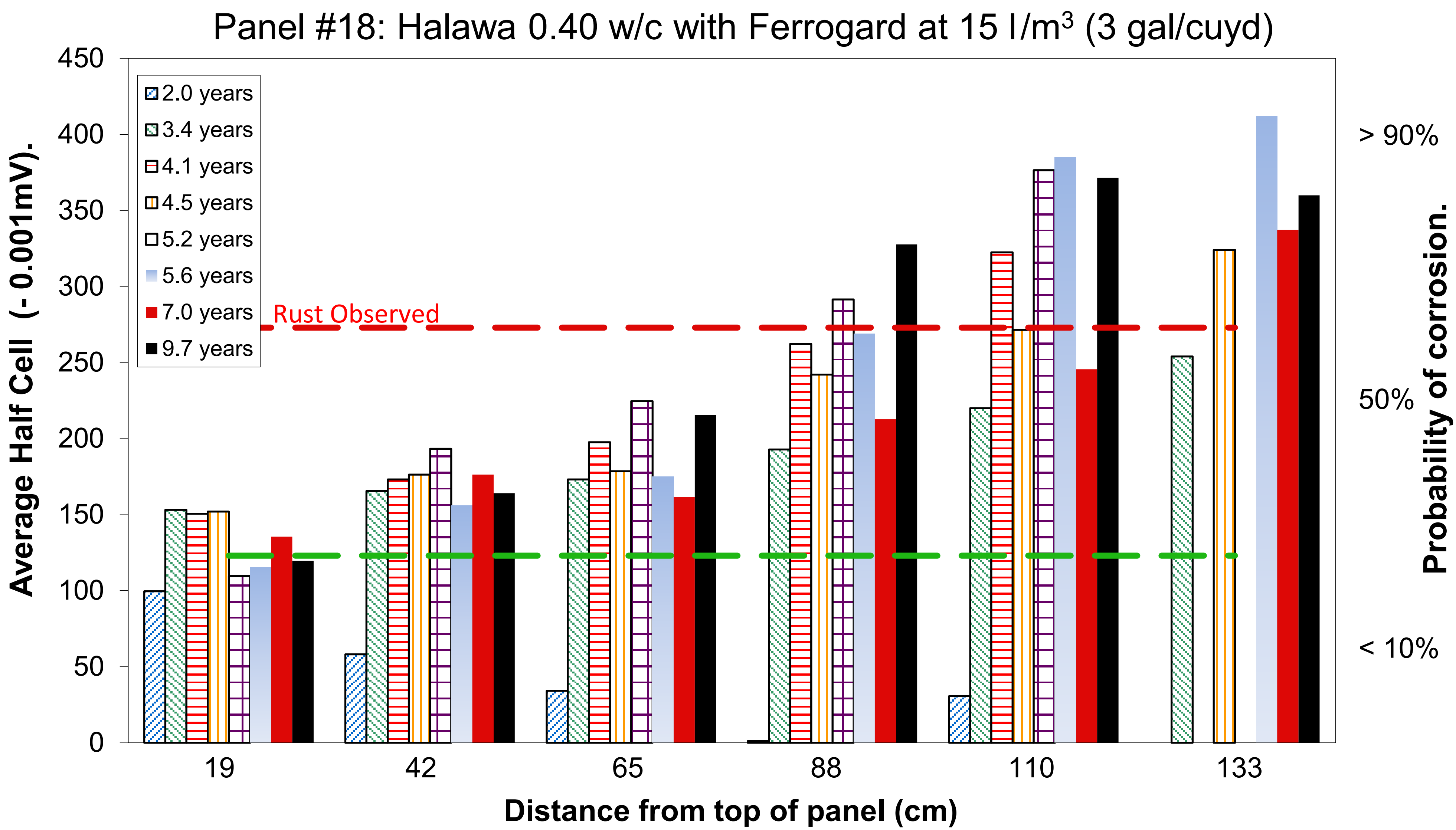
Panel 15: Kapaa 0.40 w/c; 5 *l*/m^3 Rheocrete



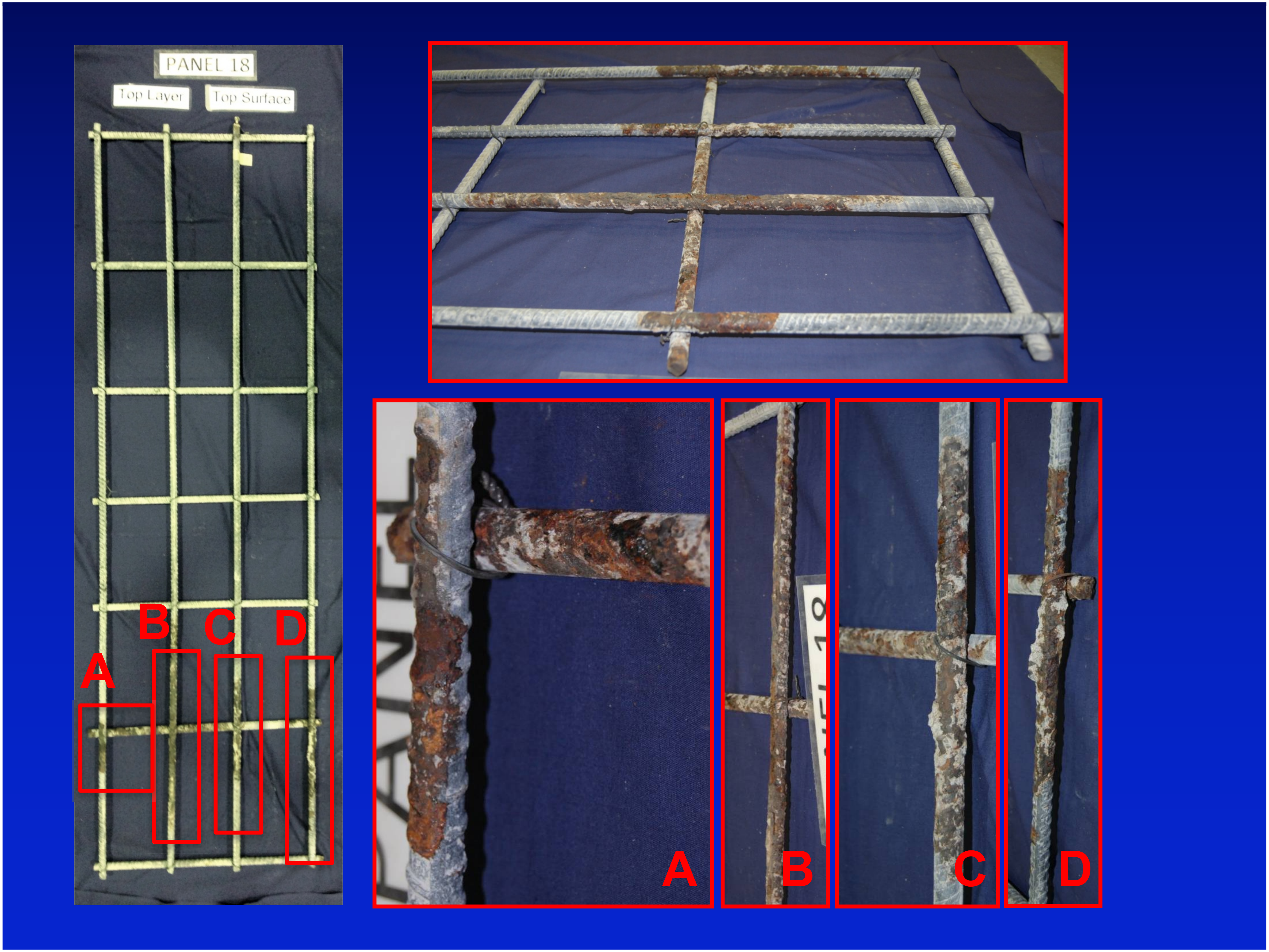
Panel 15: Kapaa 0.40 w/c; 5 l/m^3 Rheocrete


PANEL 15
Top Layer
Top Surface
PANEL 15

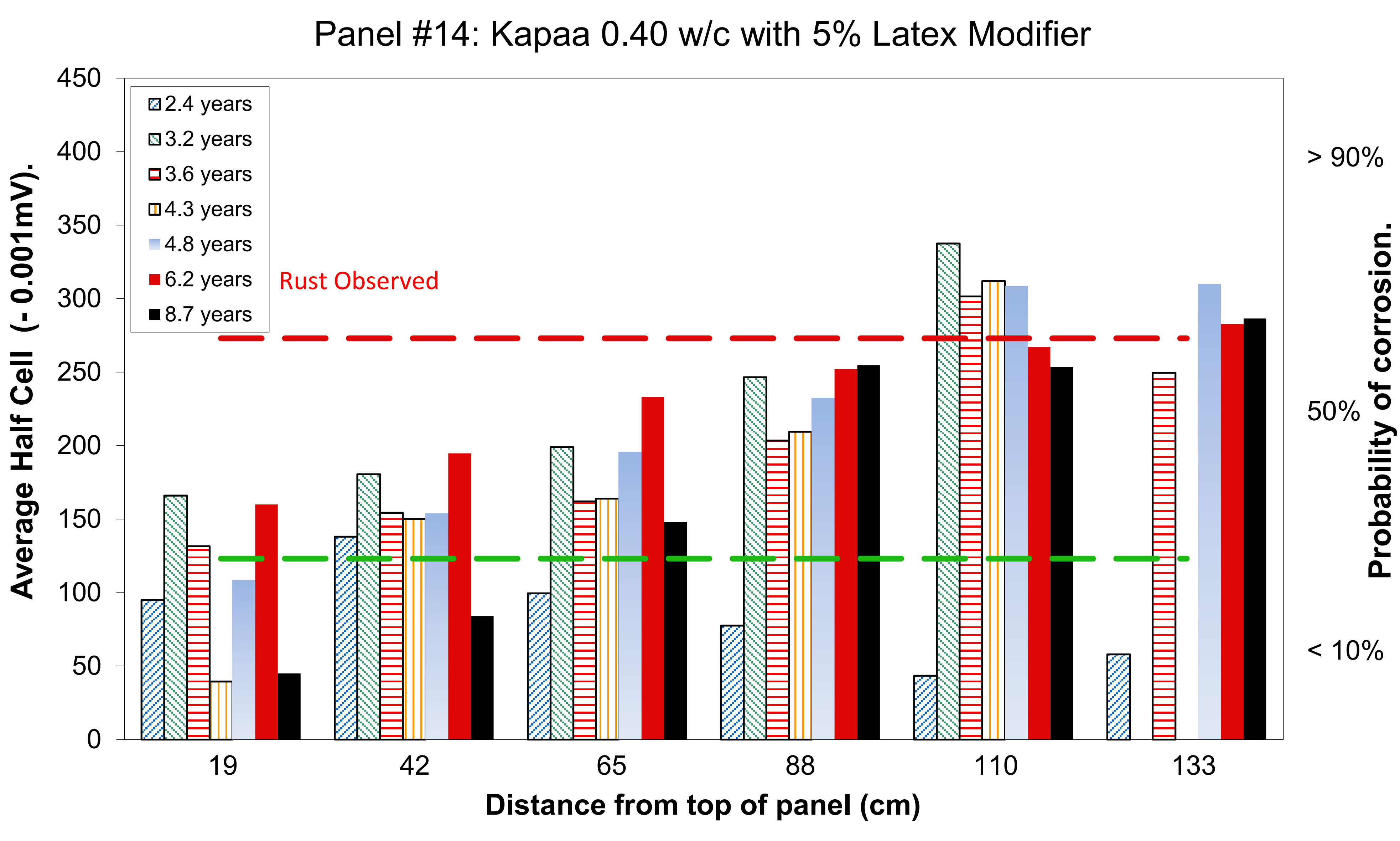
Panel 18: Halawa 0.40 w/c; 15 *l*/m³ Ferrogard



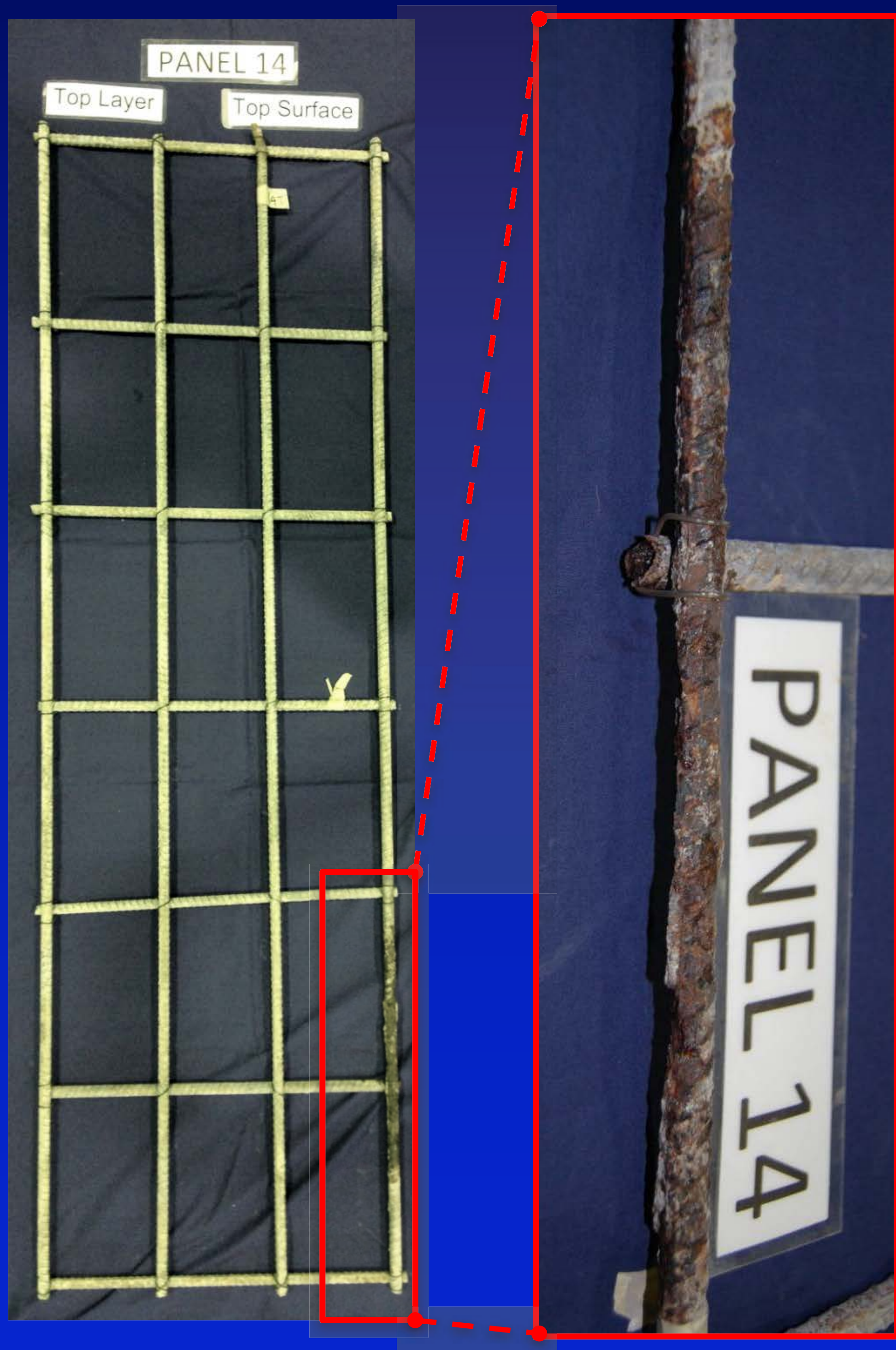
Panel 18: Halawa 0.40 w/c; 15 l/m^3 Ferrogard


PANEL 18
Top Layer
Top Surface
A
B
C
D
A
B
C
D

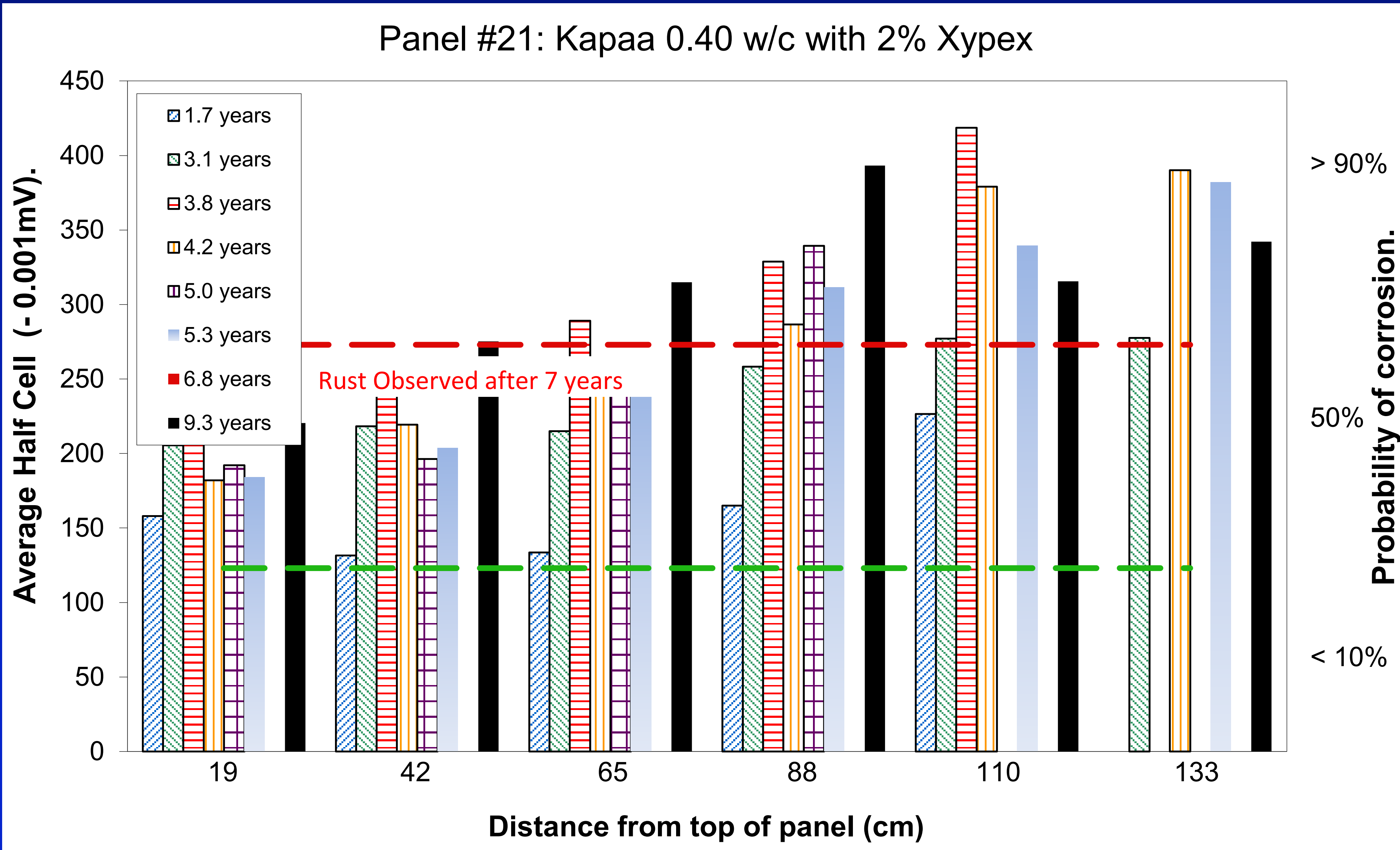
Panel 14: Kapaa 0.40 w/c; 5% Latex Modifier



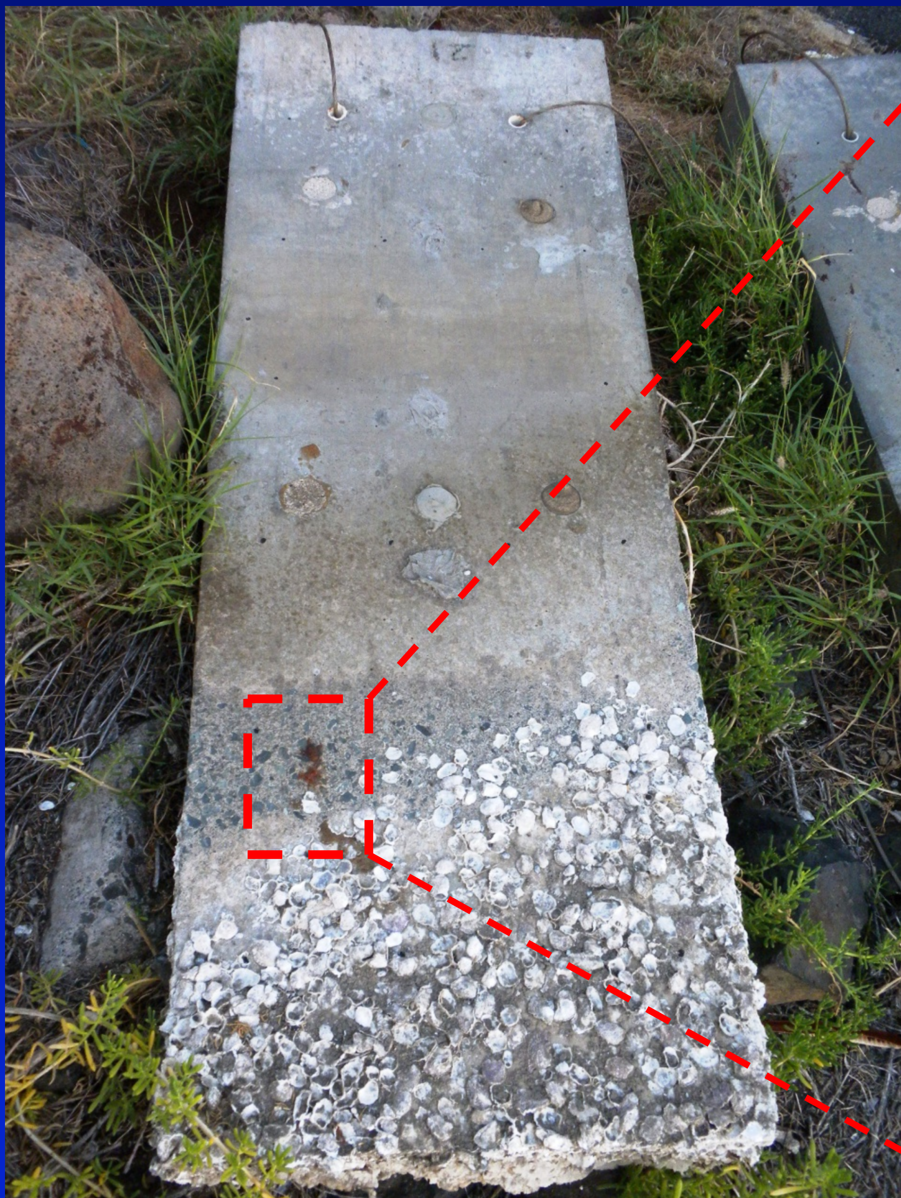
Panel 14: Kapaa 0.40 w/c; 5% Latex Modifier

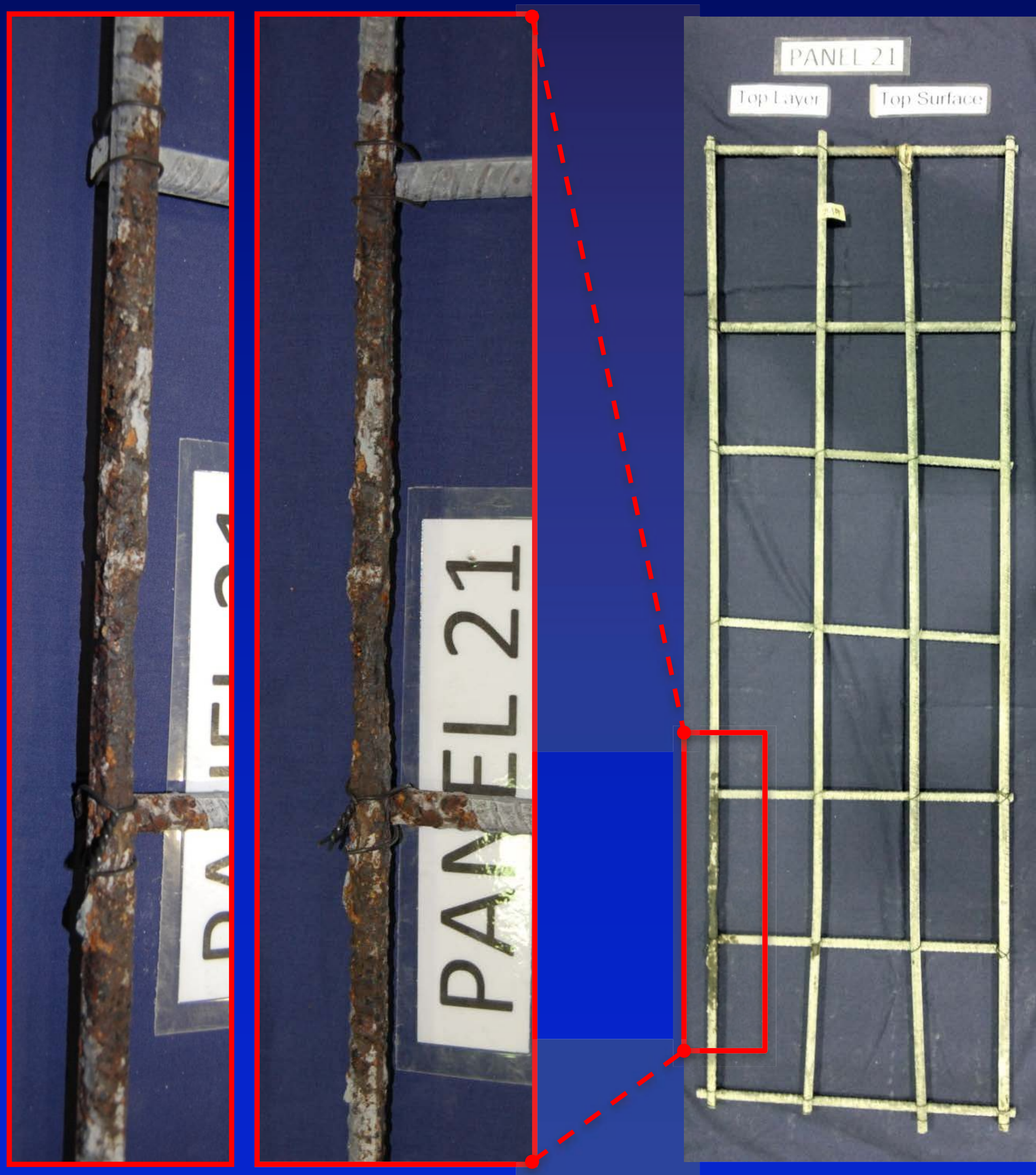

PANEL 14
Top Layer
Top Surface
PANEL 14

Panel 21: Kapaa 0.40 w/c; 2% Xypex

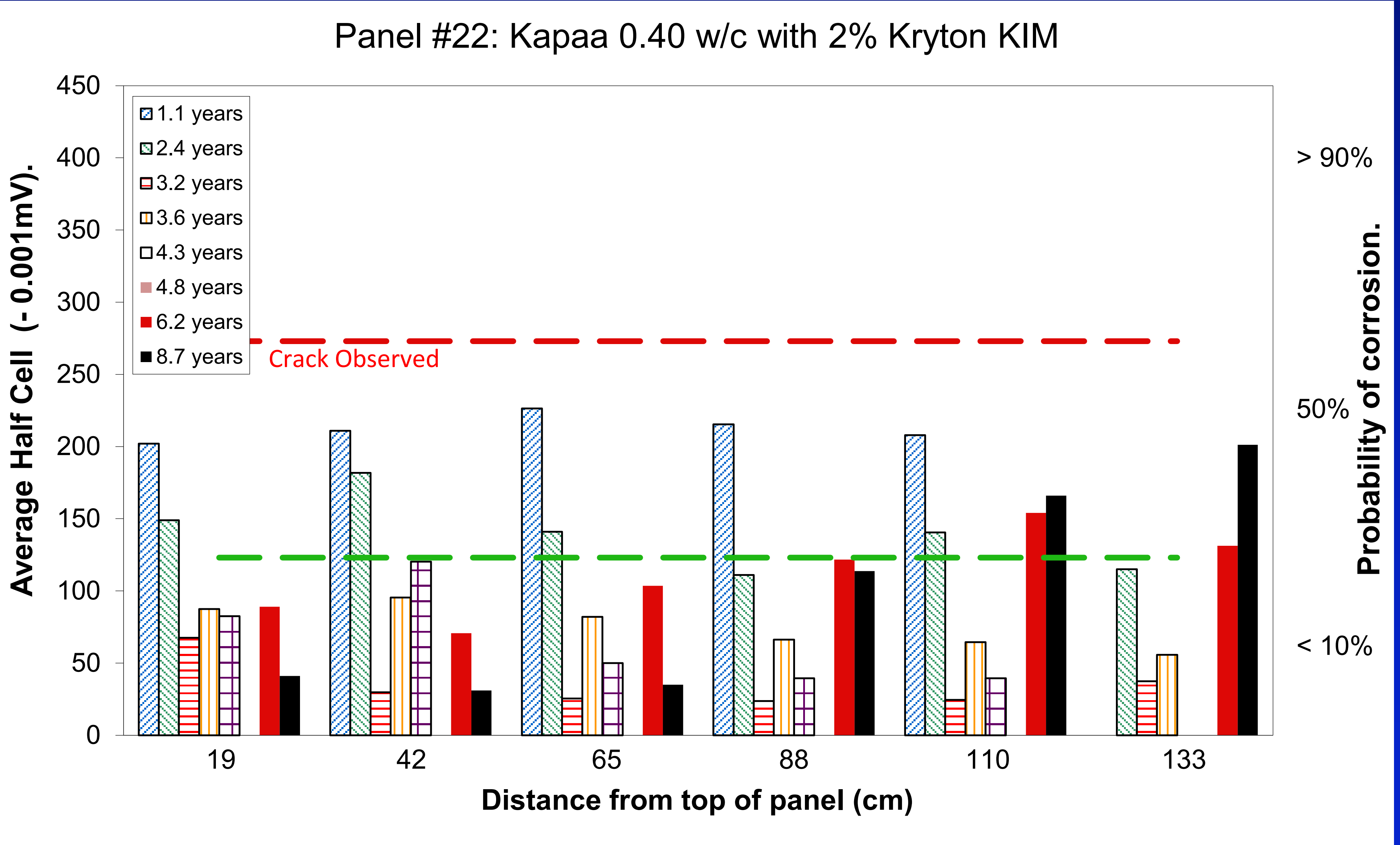


Panel 21: Kapaa 0.40 w/c; 2% Xypex



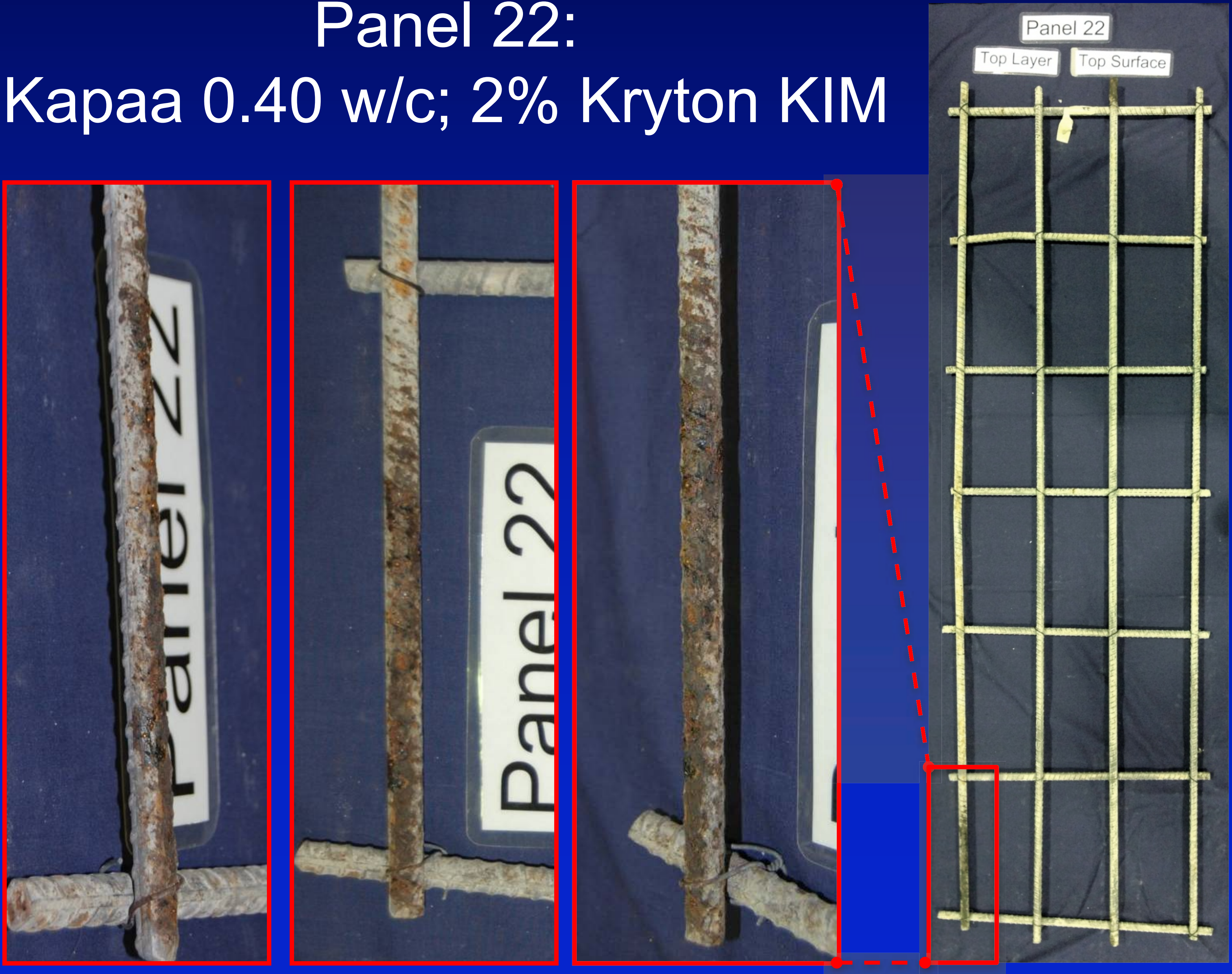

PANEL 21
Top Layer
Top Surface

Panel 22: Kapaa 0.40 w/c; 2% Kryton KIM



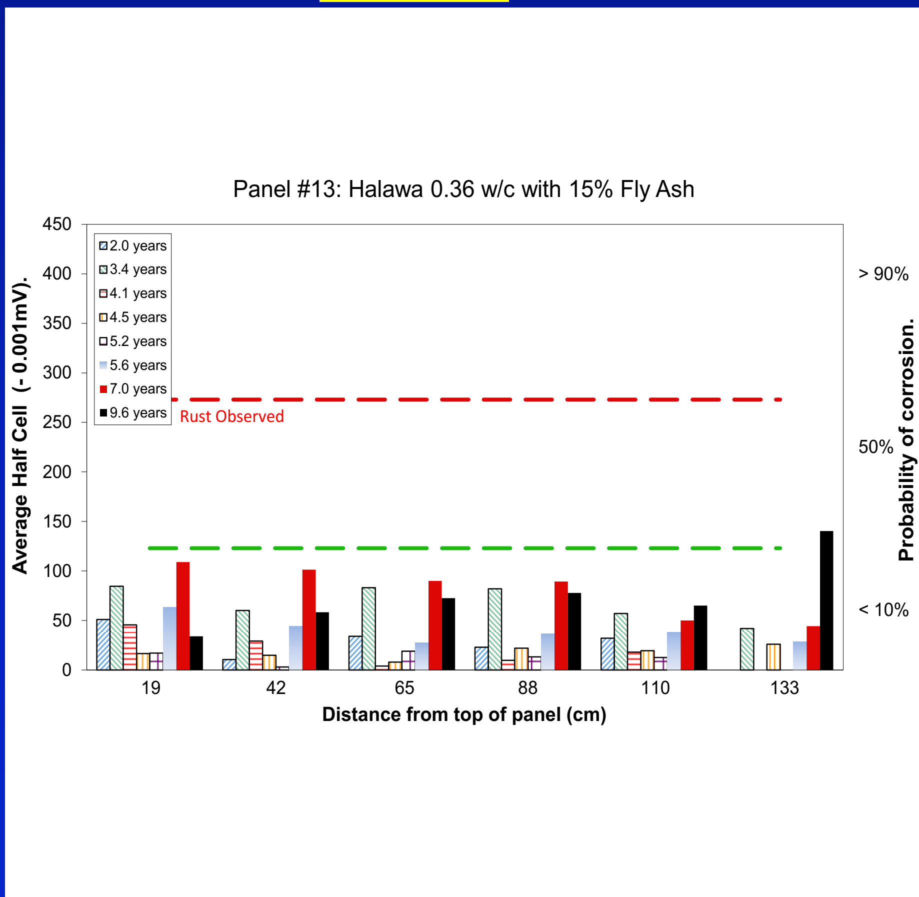
Panel 22: Kapaa 0.40 w/c; 2% Kryton KIM

Panel 22:
Kapaa 0.40 w/c; 2% Kryton KIM

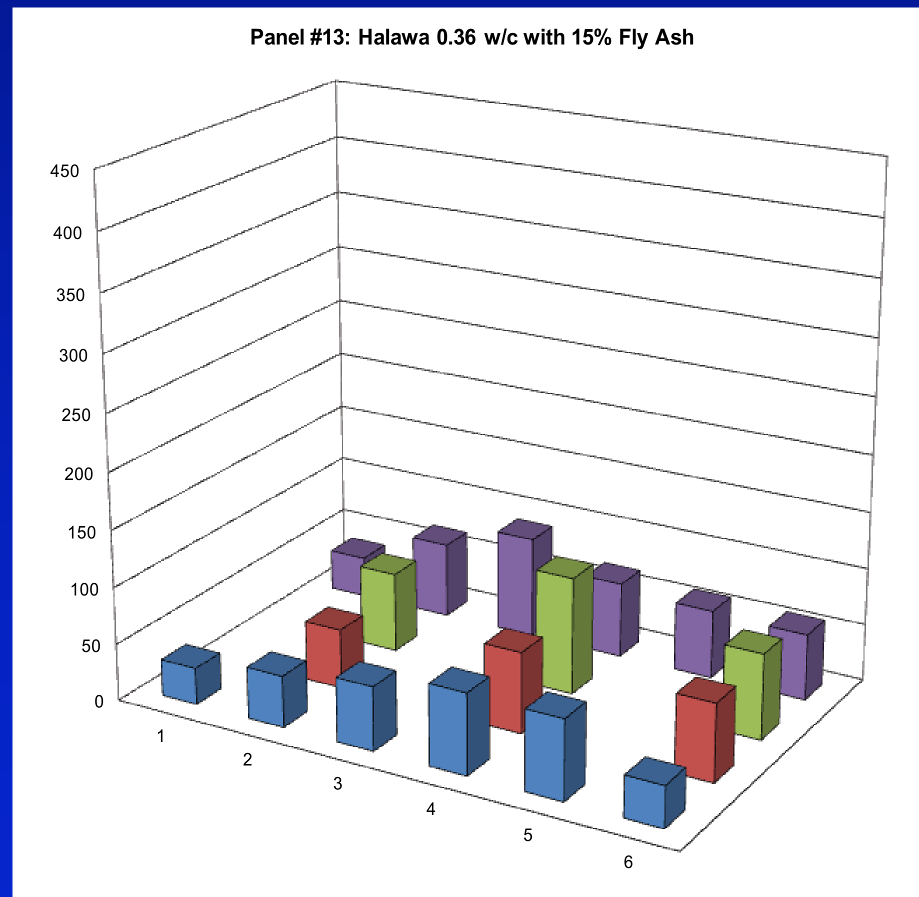


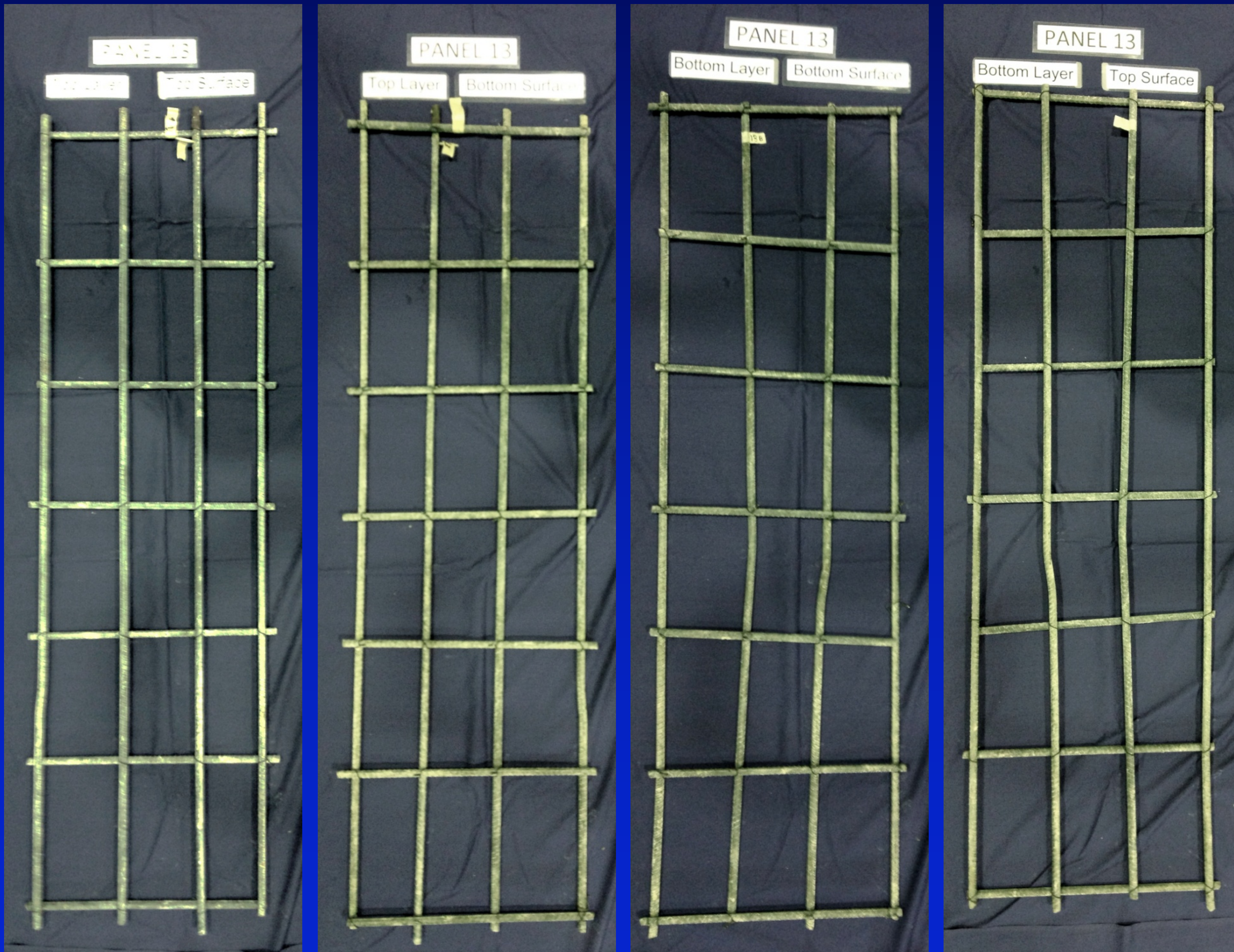
Panel 13: Halawa (0.36 w/cm) 15% Fly Ash

Half-Cell Potential Various Years

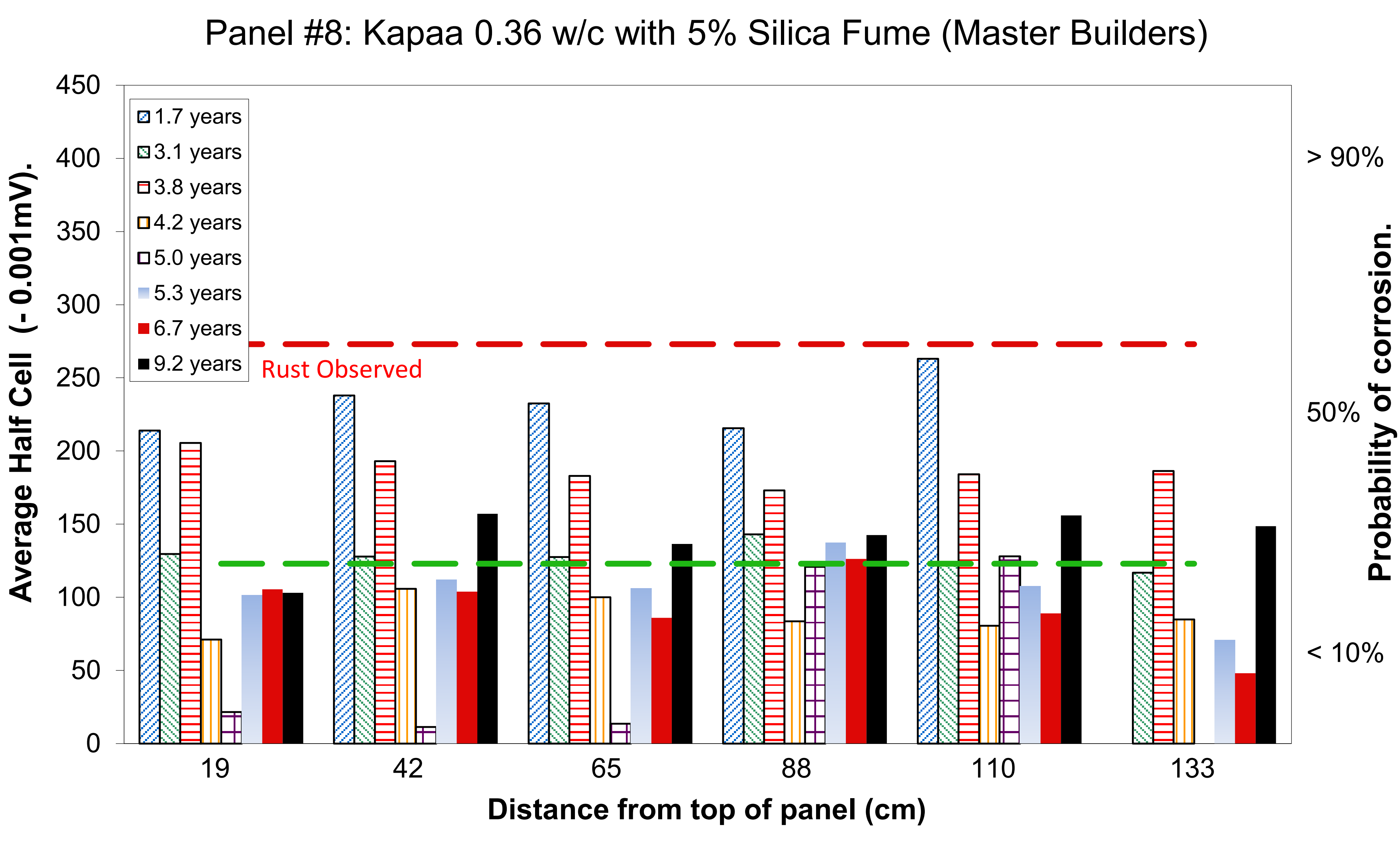


Half-Cell potential at 9.6 years

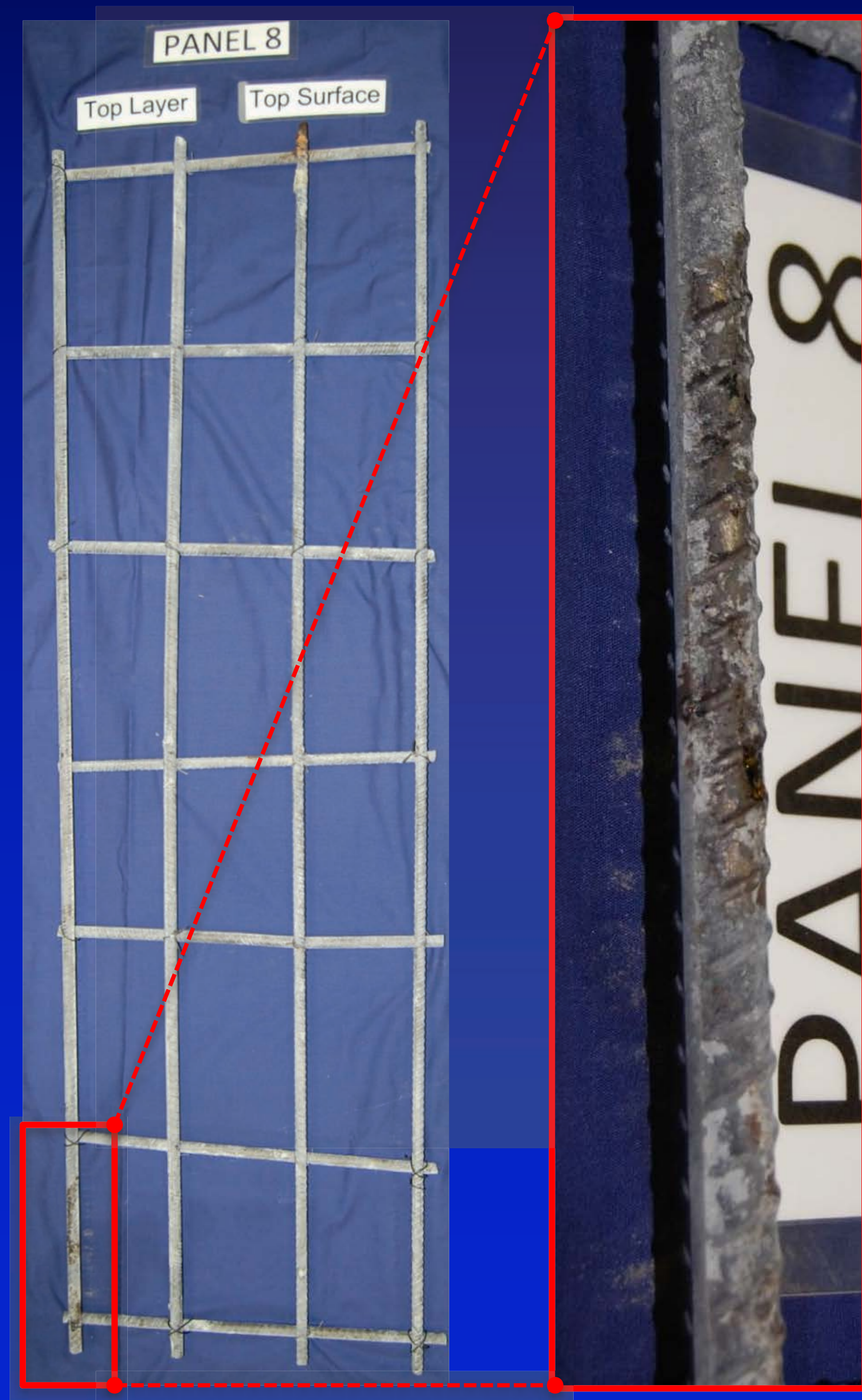



PANEL 13
Top Layer
Bottom Surface
PANEL 13
Bottom Layer
Bottom Surface
PANEL 13
Bottom Layer
Top Surface

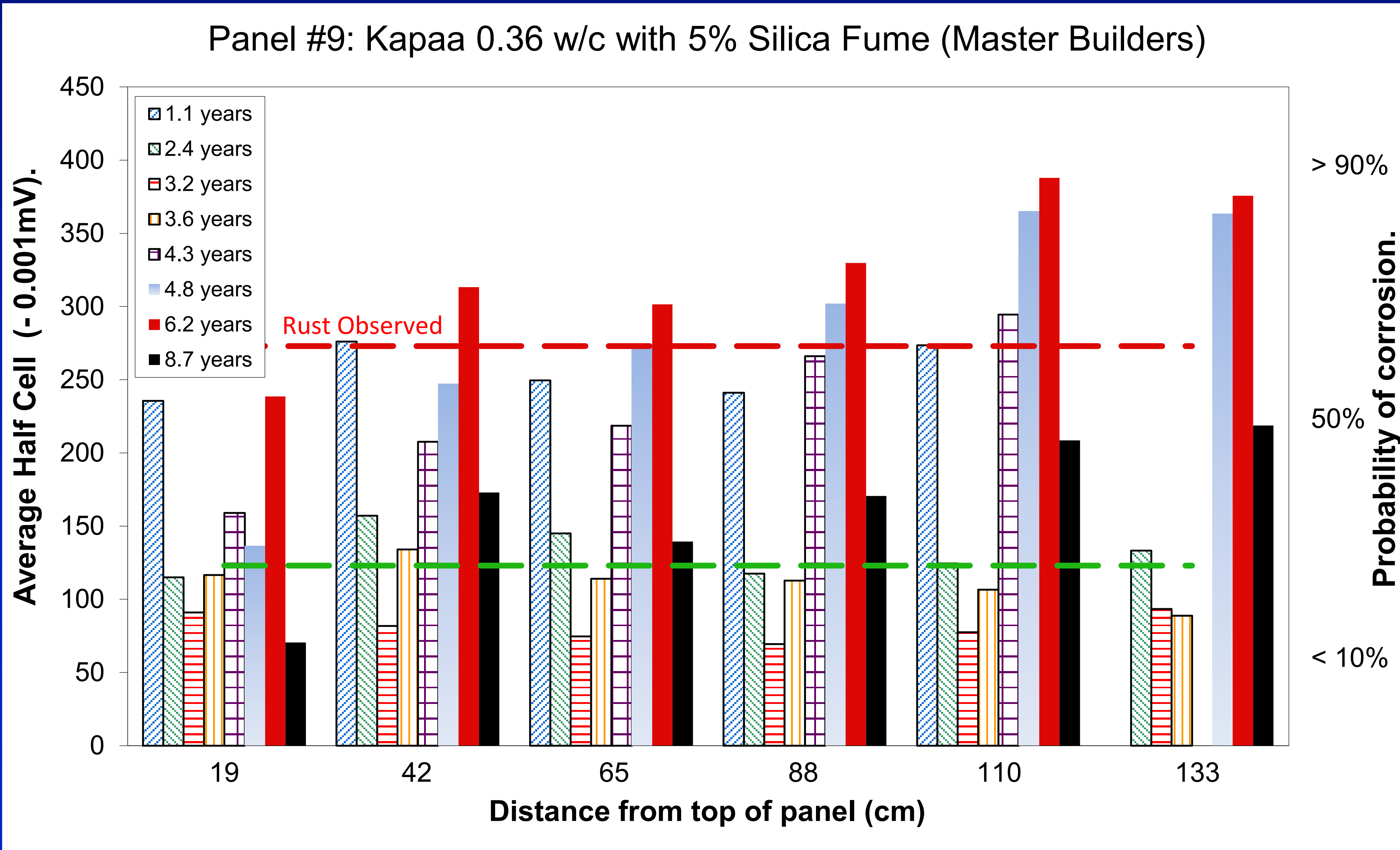
Panel 8: Kapaa 0.36 w/c; 5% Silica Fume



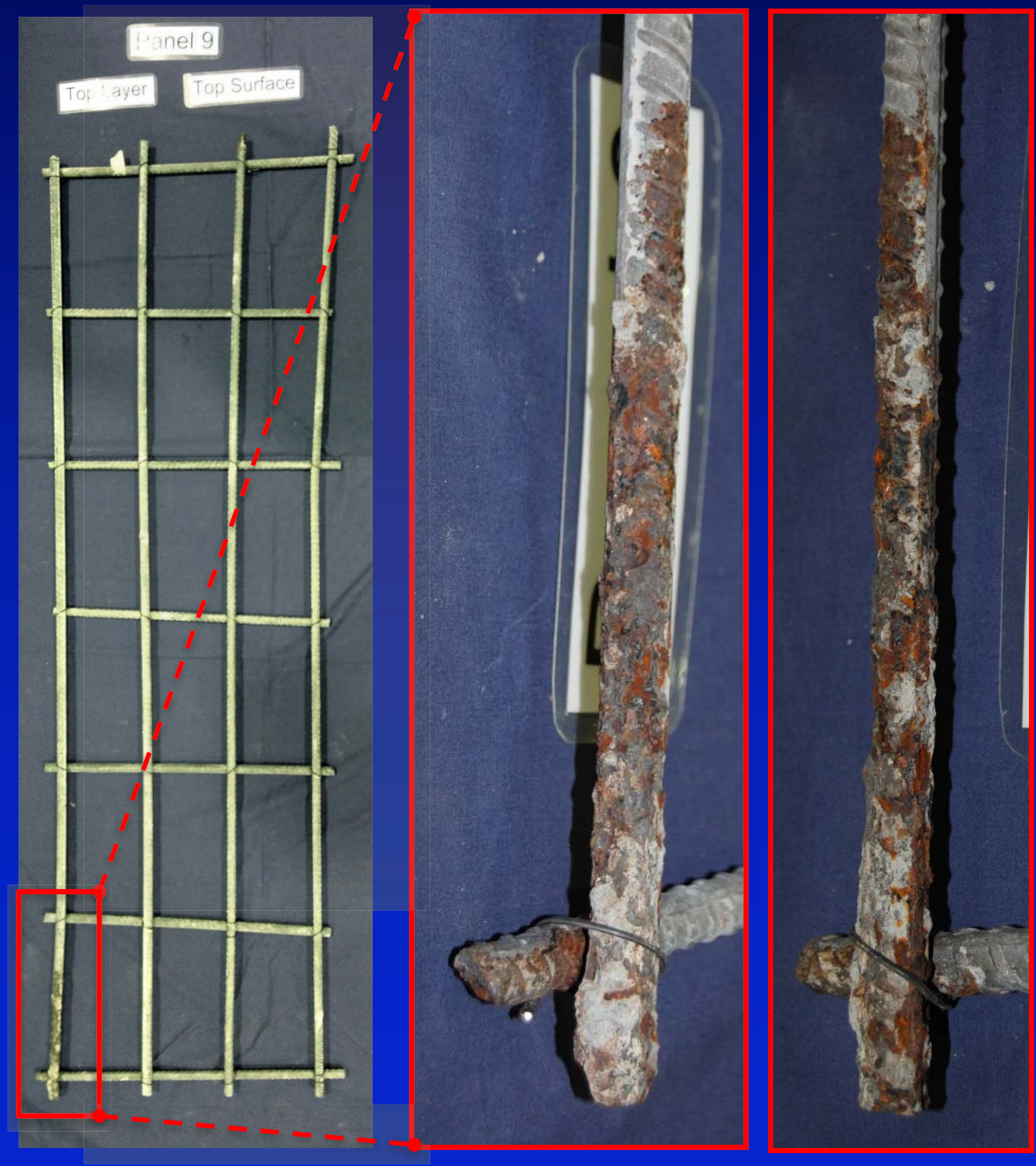
Panel 8: Kapaa 0.36 w/c; 5% Silica Fume

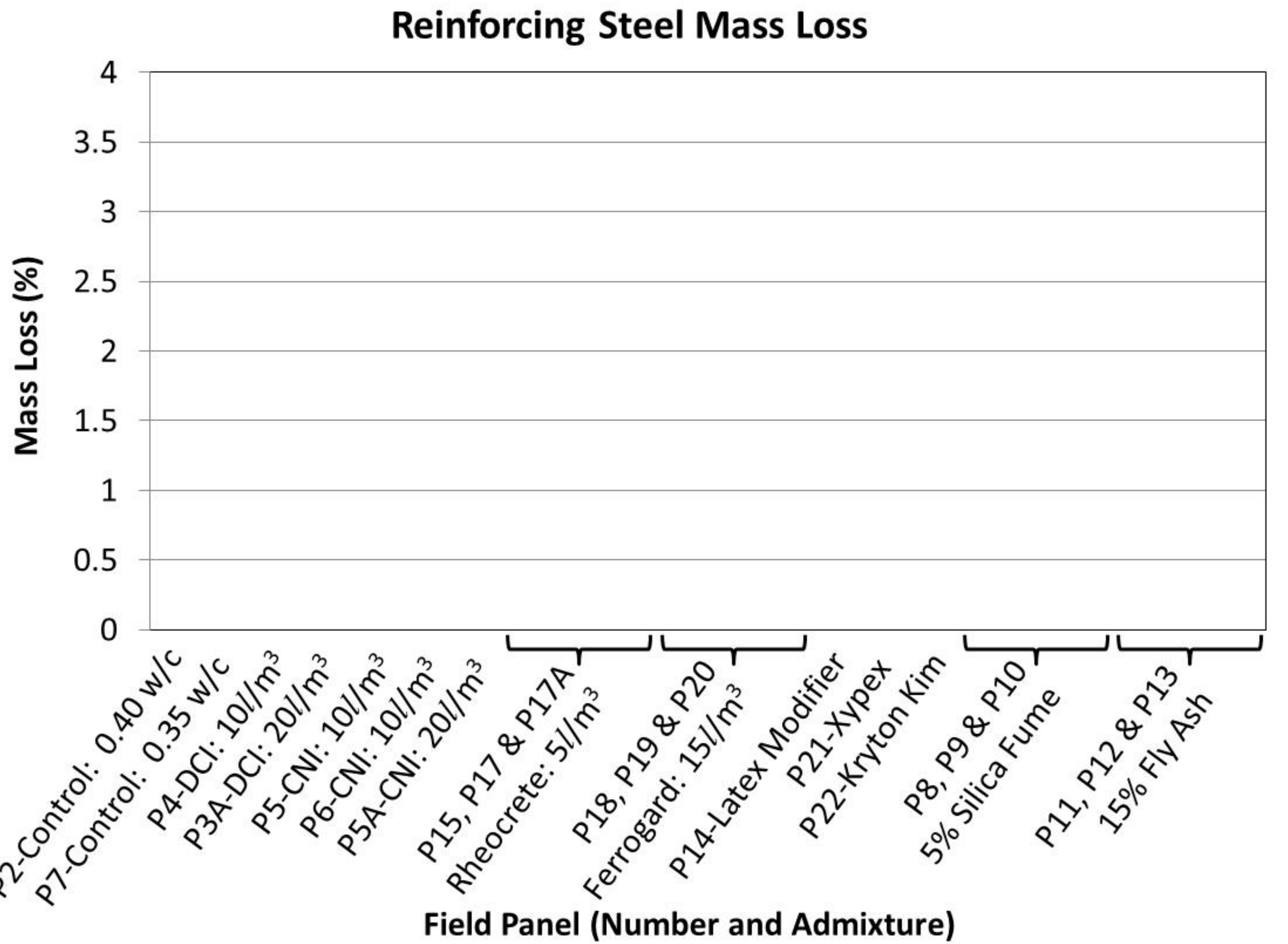

PANEL 8
Top Layer
Top Surface

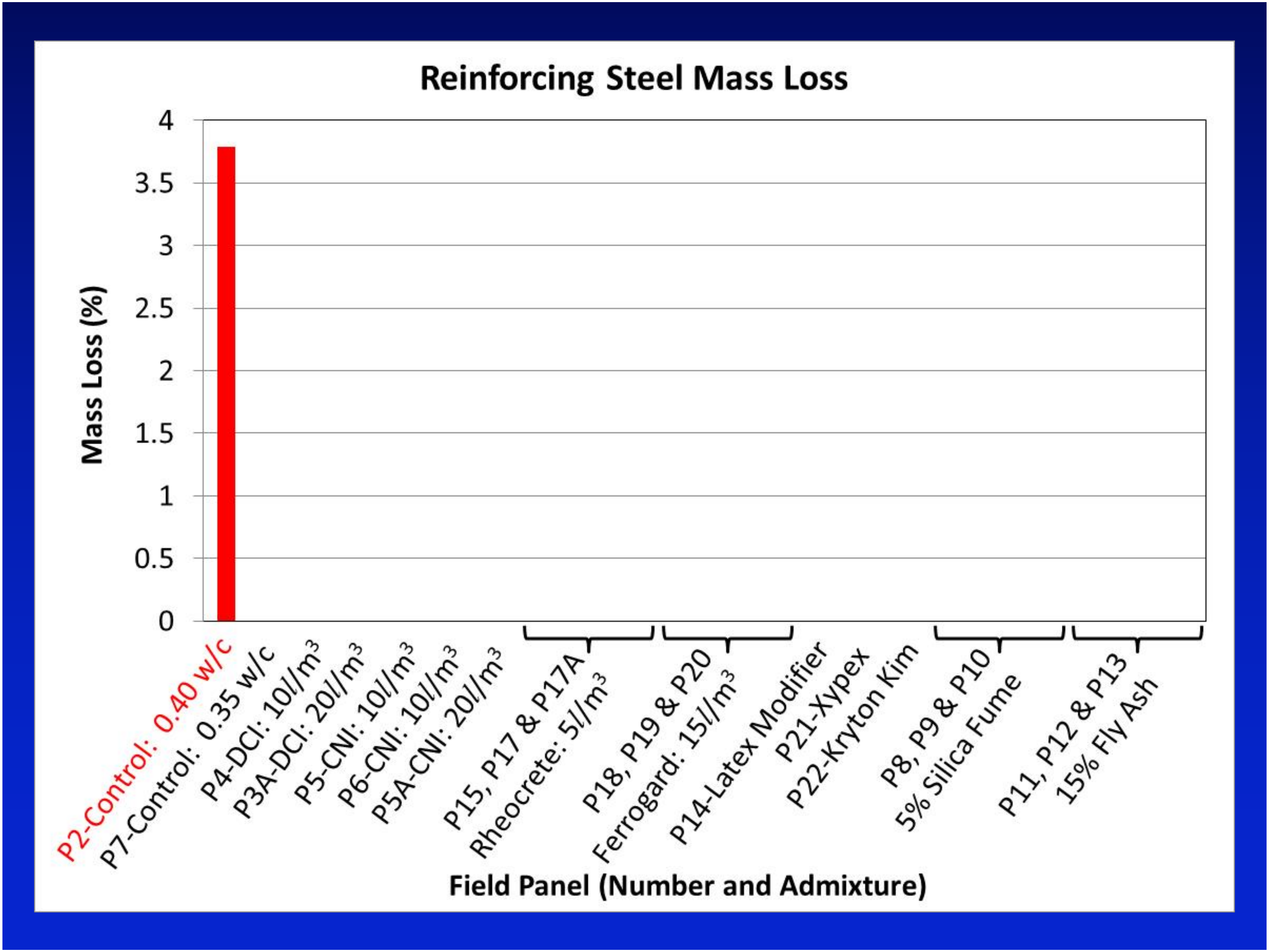
Panel 9: Kapaa 0.36 w/c; 5% Silica Fume



Panel 9: Kapaa 0.36 w/c; 5% Silica Fume


Panel 9
Top Layer
Top Surface


Reinforcing Steel Mass Loss
Mass Loss (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
P2-Control: 0.40 w/c
P7-Control: 0.35 w/c
P4-DCI: 10l/m3
P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
P5A-CNI: 20l/m3
P15, P17 & P17A
Rheocrete: 5l/m3
P18, P19 & P20
Ferrogard: 15l/m3
P14-Latex Modifier
P21-Xypex
P22-Kryton Kim
P8, P9 & P10
5% Silica Fume
P11, P12 & P13
15% Fly Ash
Field Panel (Number and Admixture)



Reinforcing Steel Mass Loss
Mass Loss (%)
4
3.5
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P2-Control: 0.40 w/c
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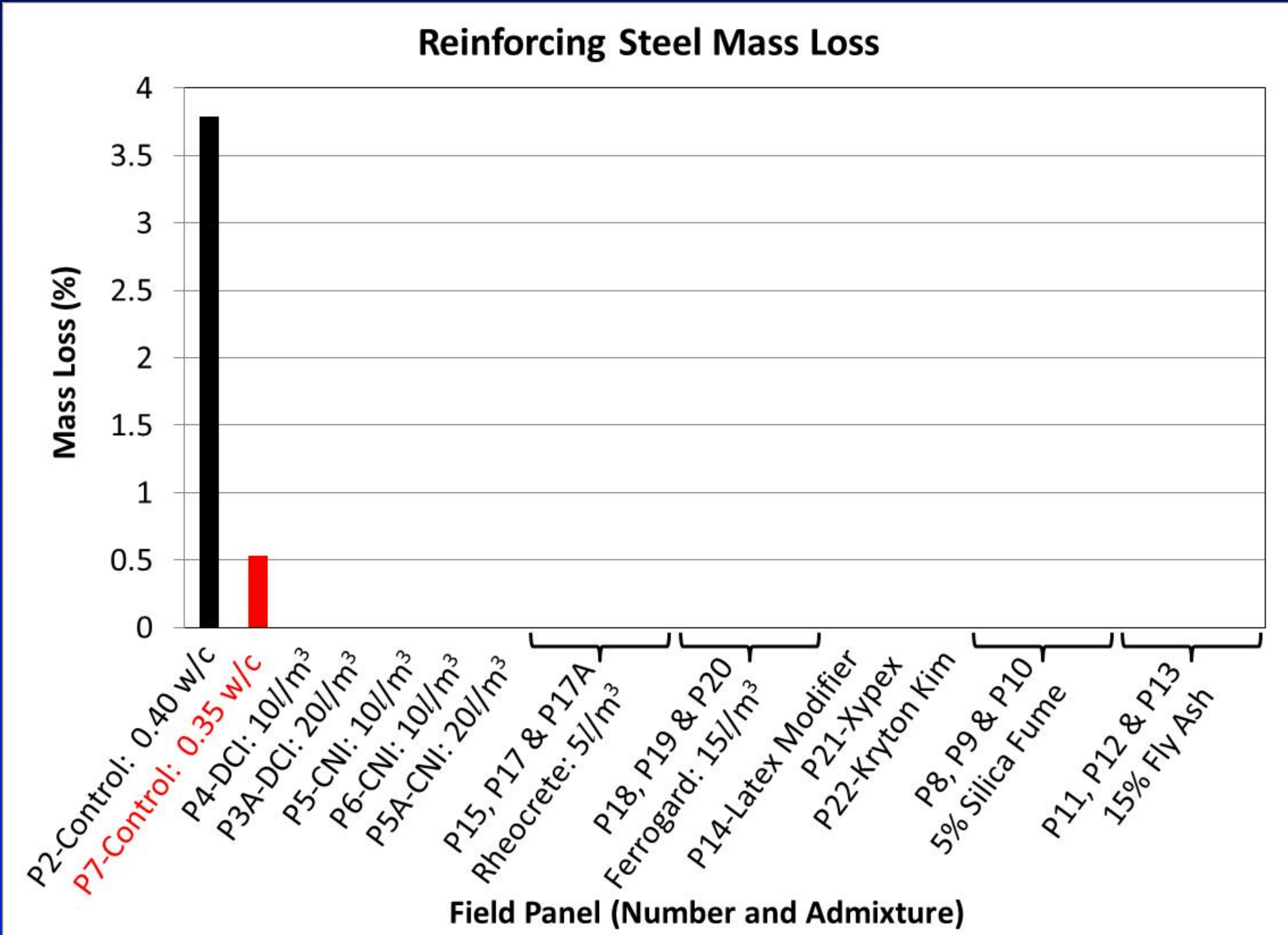
P5-CNI: 10l/m3
P6-CNI: 10l/m3
P5A-CNI: 20l/m3
P15, P17 & P17A
Rheocrete: 5l/m3
P18, P19 & P20
Ferrogard: 15l/m3
P14-Latex Modifier
P21-Xypex
P22-Kryton Kim
P8, P9 & P10
5% Silica Fume
P11, P12 & P13
15% Fly Ash
Field Panel (Number and Admixture)



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4
3.5
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P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
P5A-CNI: 20l/m3
P15, P17 & P17A
Rheocrete: 5l/m3
P18, P19 & P20
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P8, P9 & P10
5% Silica Fume
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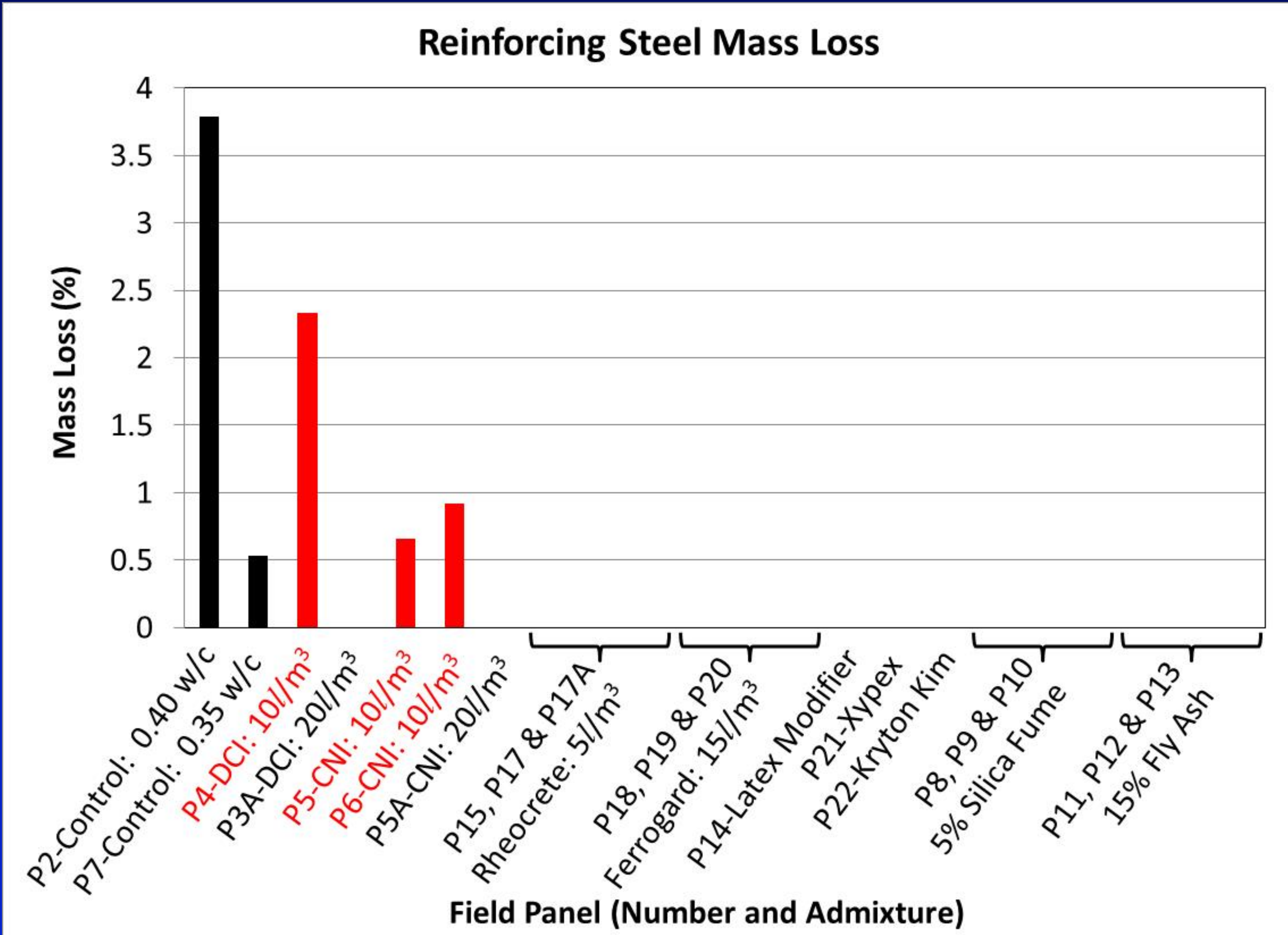
Field Panel (Number and Admixture)



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P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
P5A-CNI: 20l/m3
P15, P17 & P17A
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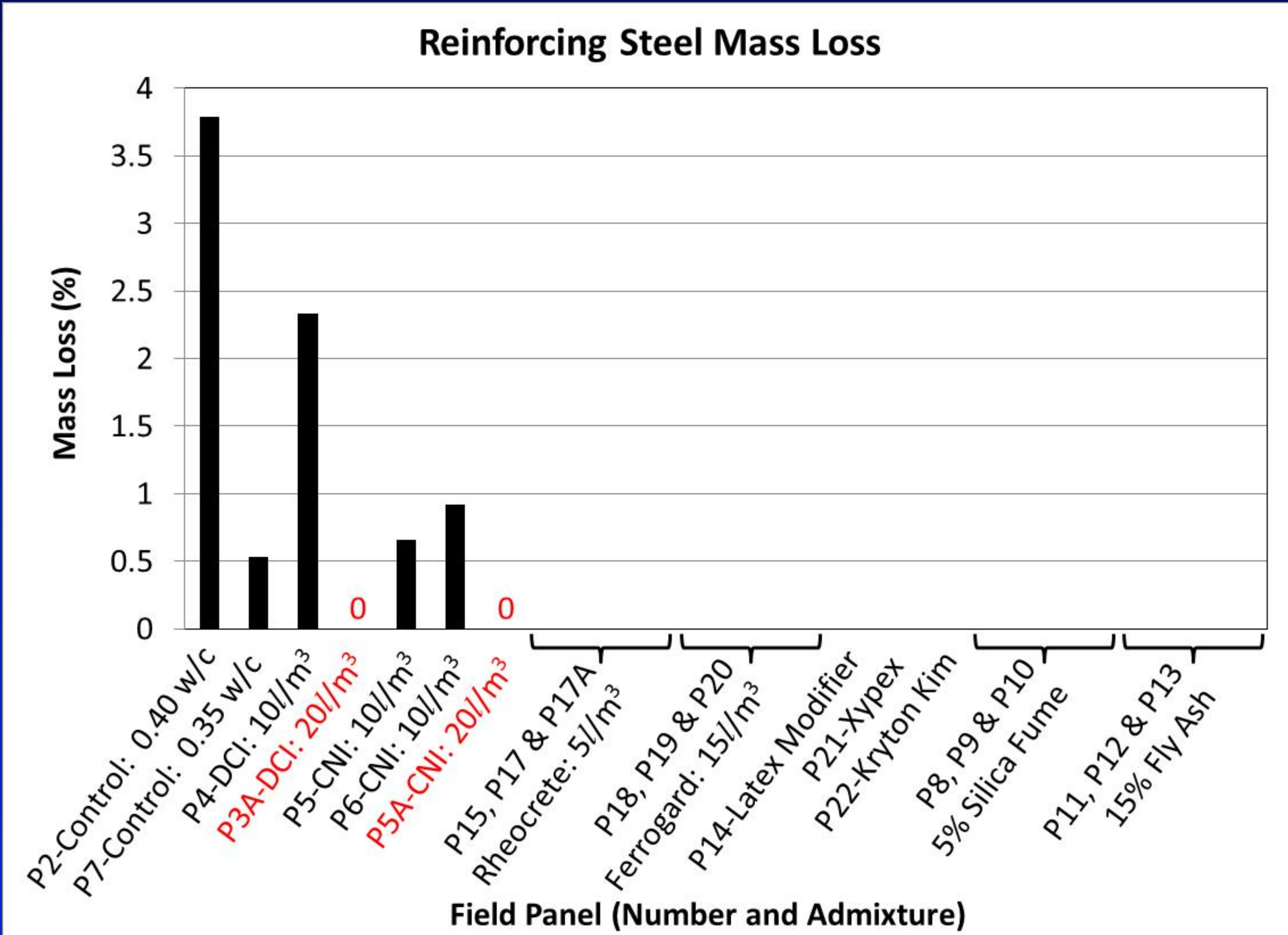

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3.5
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1.5
1
0.5
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P2-Control: 0.40 w/c
P7-Control: 0.35 w/c
P4-DCI: 10l/m³
P3A-DCI: 20l/m³
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P15, P17 & P17A
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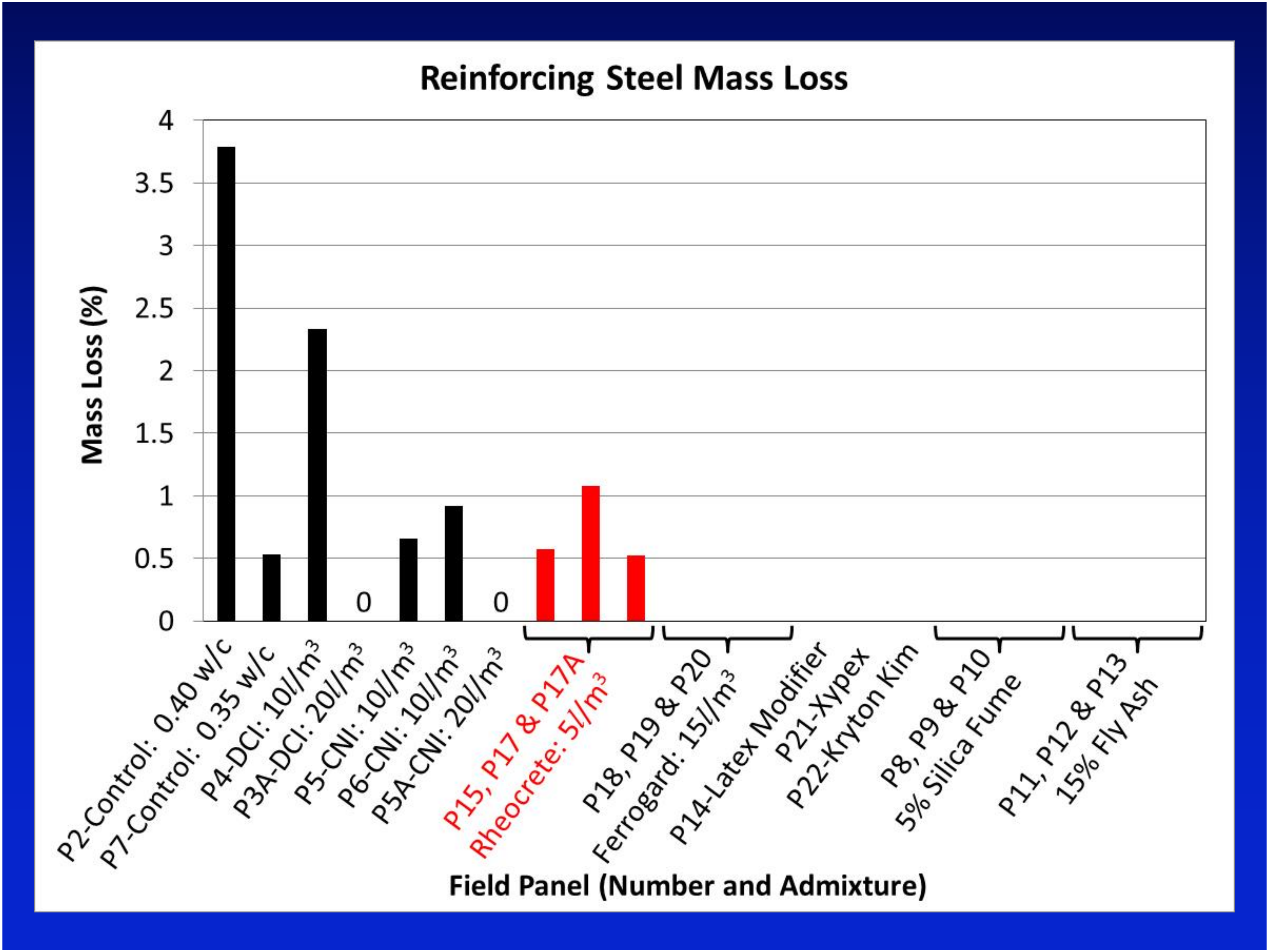

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Mass Loss (%)
4
3.5
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2.5
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1.5
1
0.5
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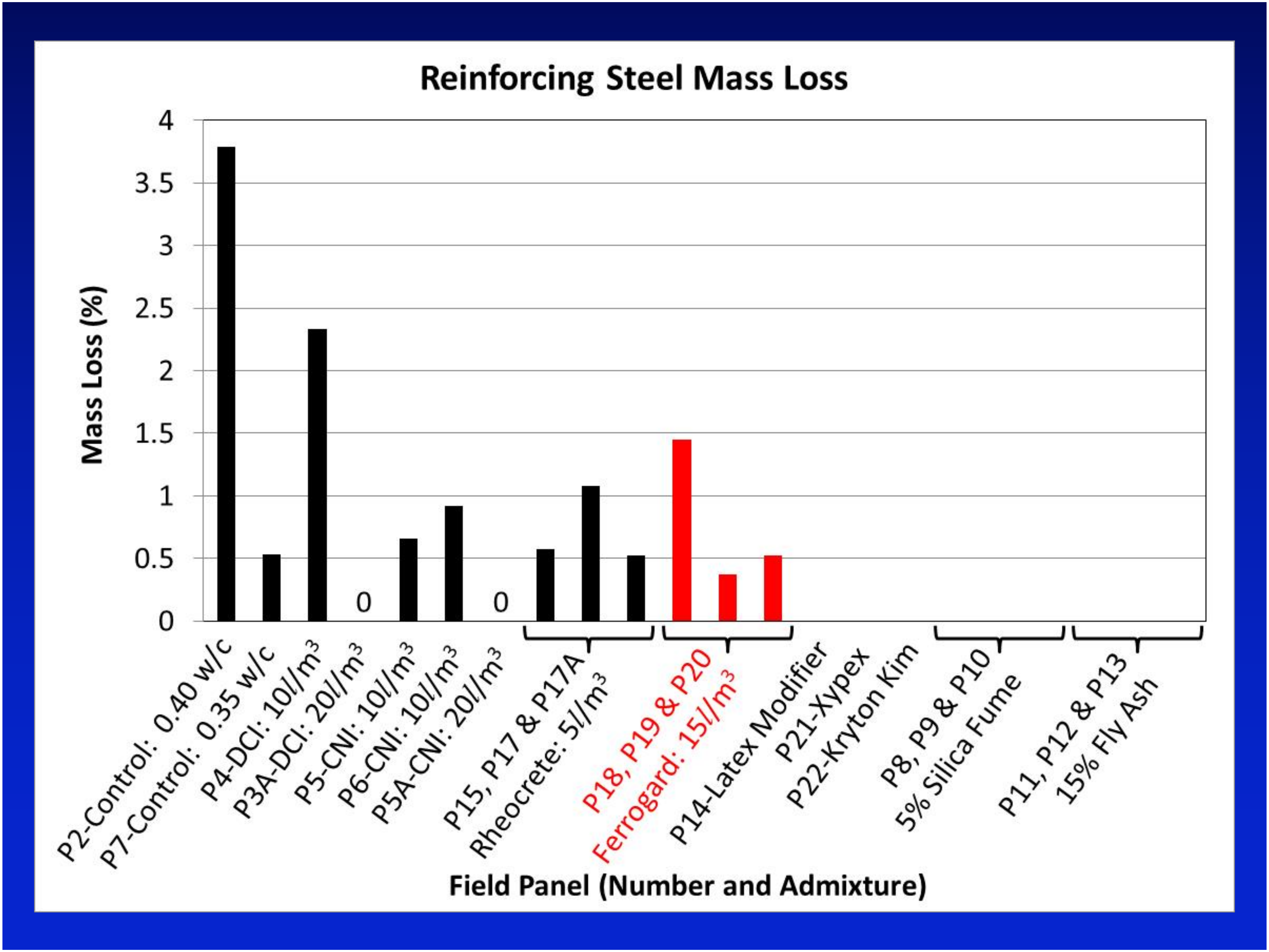
Field Panel (Number and Admixture)



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Mass Loss (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0
P2-Control: 0.40 w/c
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P4-DCI: 10l/m3
P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
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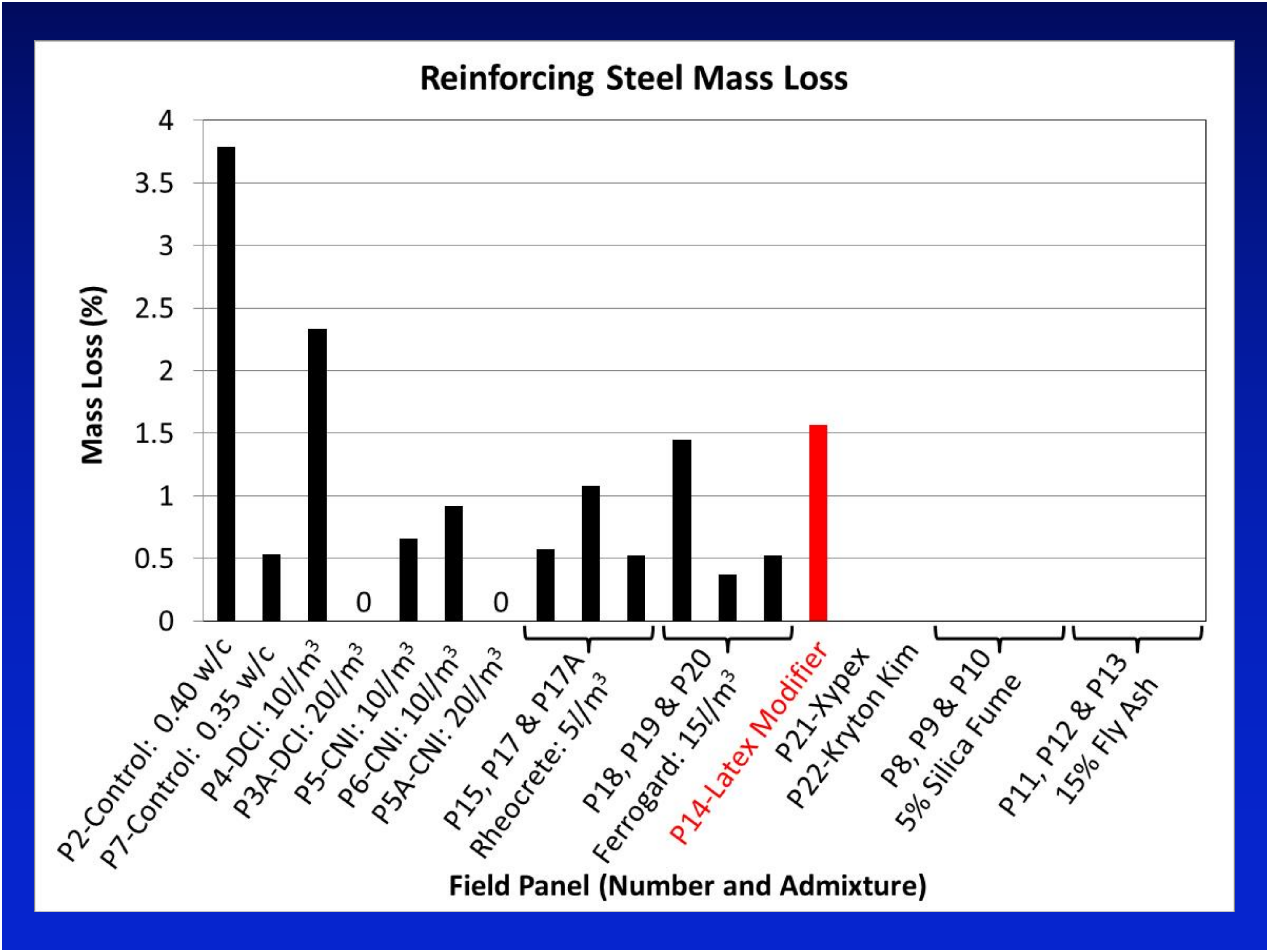
Field Panel (Number and Admixture)



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Mass Loss (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0
P2-Control: 0.40 w/c
P7-Control: 0.35 w/c
P4-DCI: 10l/m3
P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
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P15, P17 & P17A
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P18, P19 & P20
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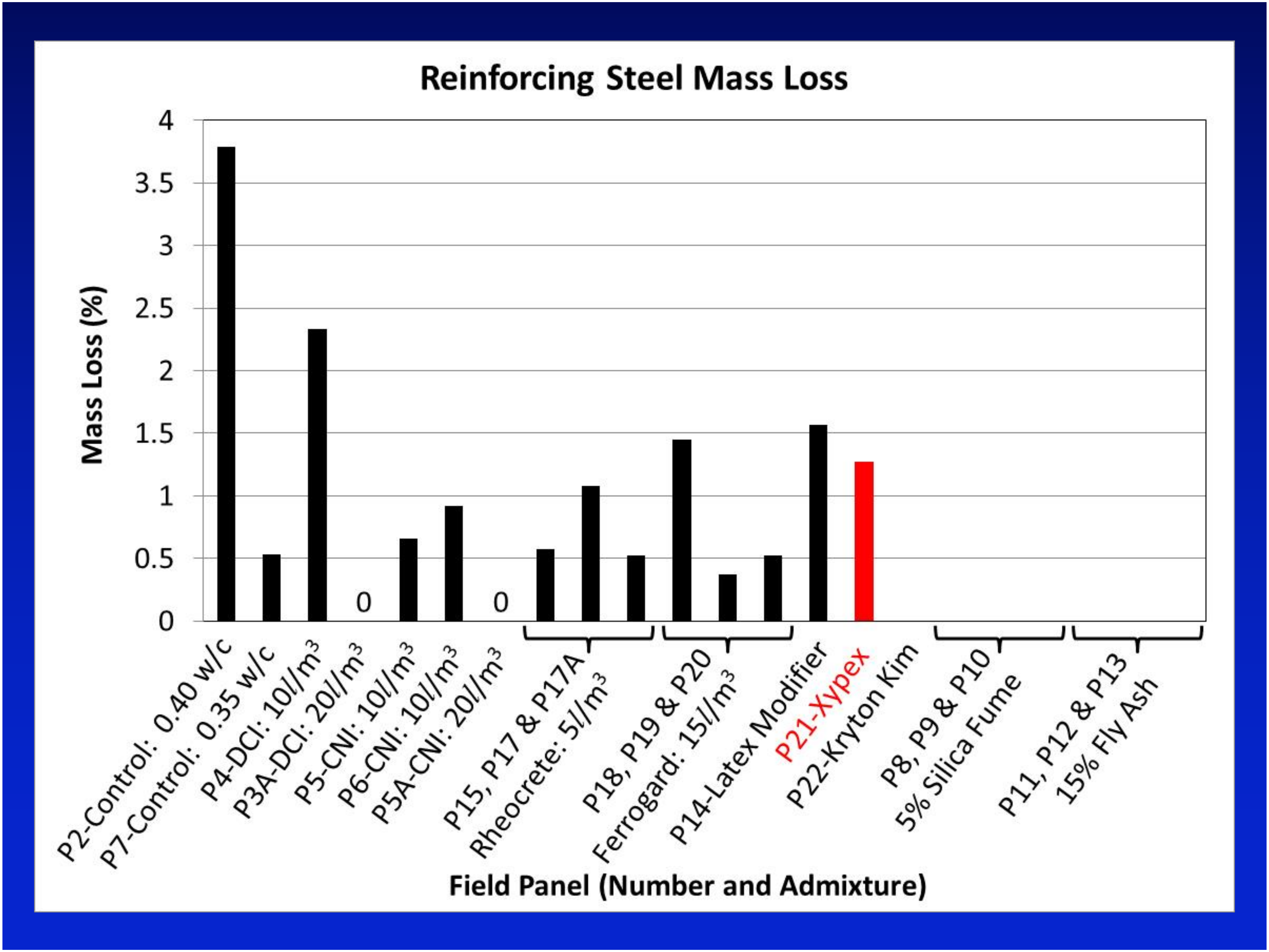
P14-Latex Modifier
P21-Xypex
P22-Kryton Kim
P8, P9 & P10
5% Silica Fume
P11, P12 & P13
15% Fly Ash
Field Panel (Number and Admixture)



Reinforcing Steel Mass Loss
Mass Loss (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0
P2-Control: 0.40 w/c
P7-Control: 0.35 w/c
P4-DCI: 10l/m3
P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
P5A-CNI: 20l/m3
P15, P17 & P17A
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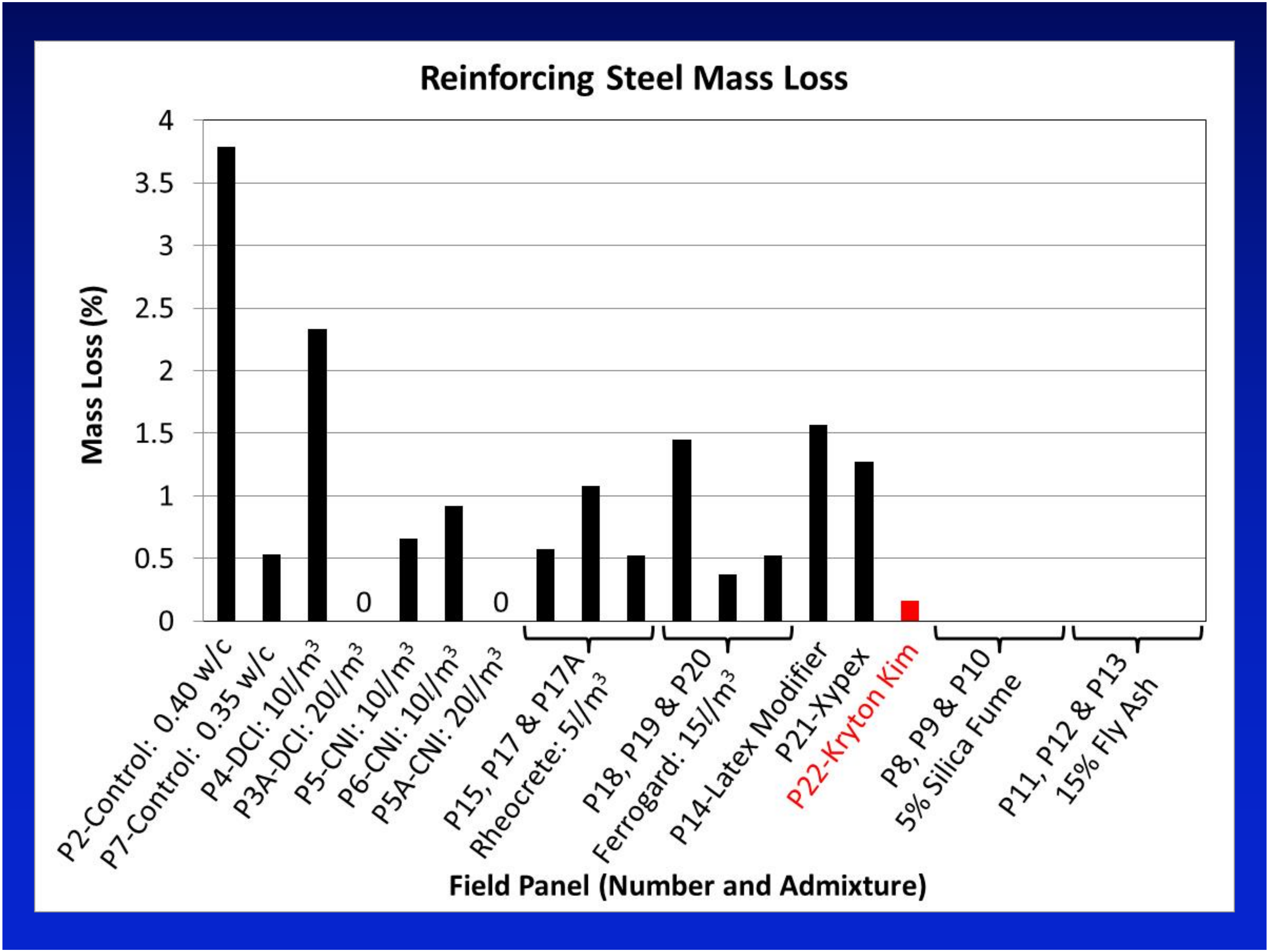
Field Panel (Number and Admixture)



Reinforcing Steel Mass Loss
Mass Loss (%)
4
3.5
3
2.5
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1.5
1
0.5
0
0
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P2-Control: 0.40 w/c
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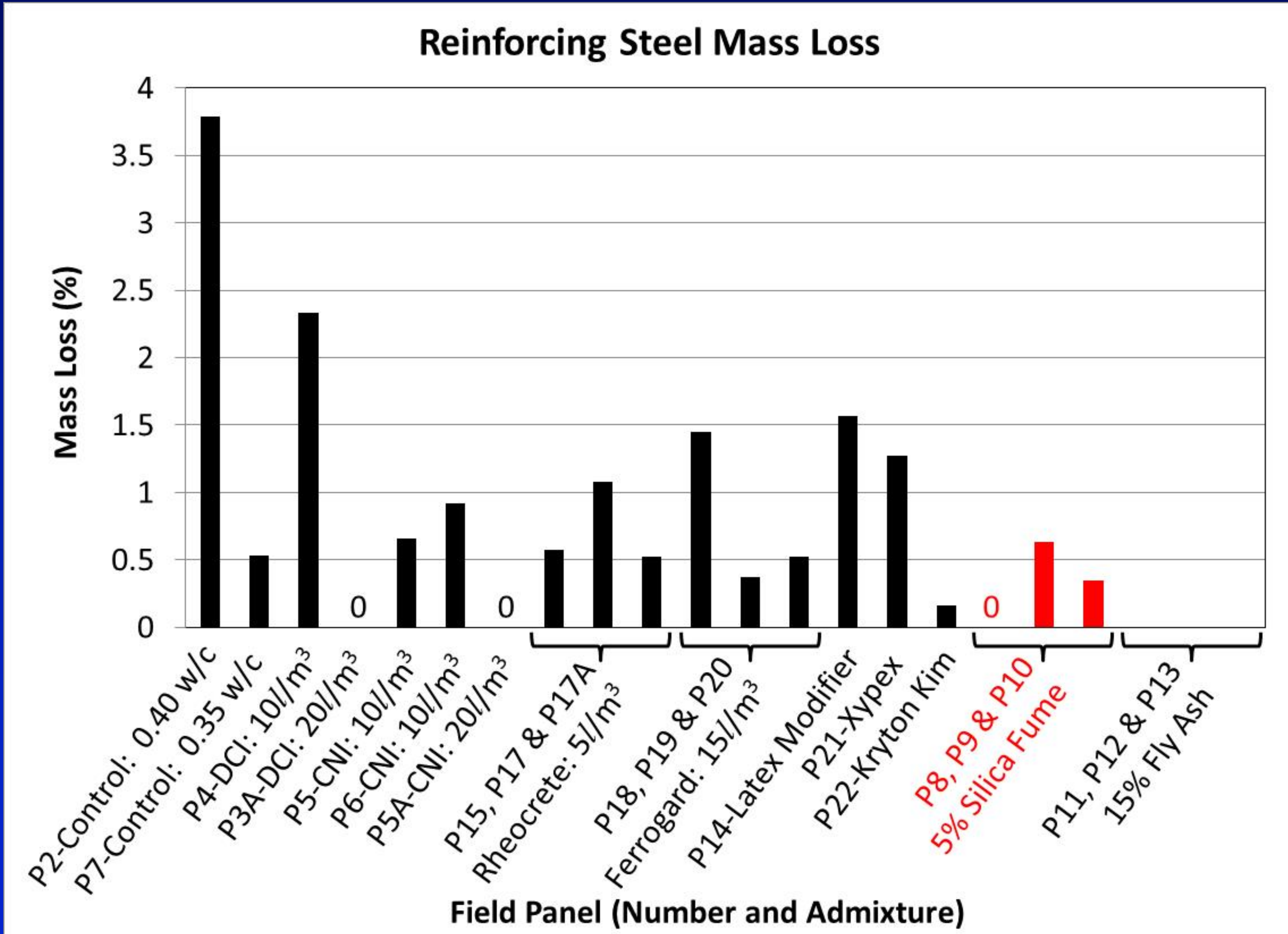
Field Panel (Number and Admixture)



Reinforcing Steel Mass Loss
Mass Loss (%)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
0
0
P2-Control: 0.40 w/c
P7-Control: 0.35 w/c
P4-DCI: 10l/m3
P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
P5A-CNI: 20l/m3
P15, P17 & P17A
Rheocrete: 5l/m3
P18, P19 & P20
Ferrogard: 15l/m3
P14-Latex Modifier
P21-Xypex
P22-Kryton Kim
P8, P9 & P10
5% Silica Fume
P11, P12 & P13
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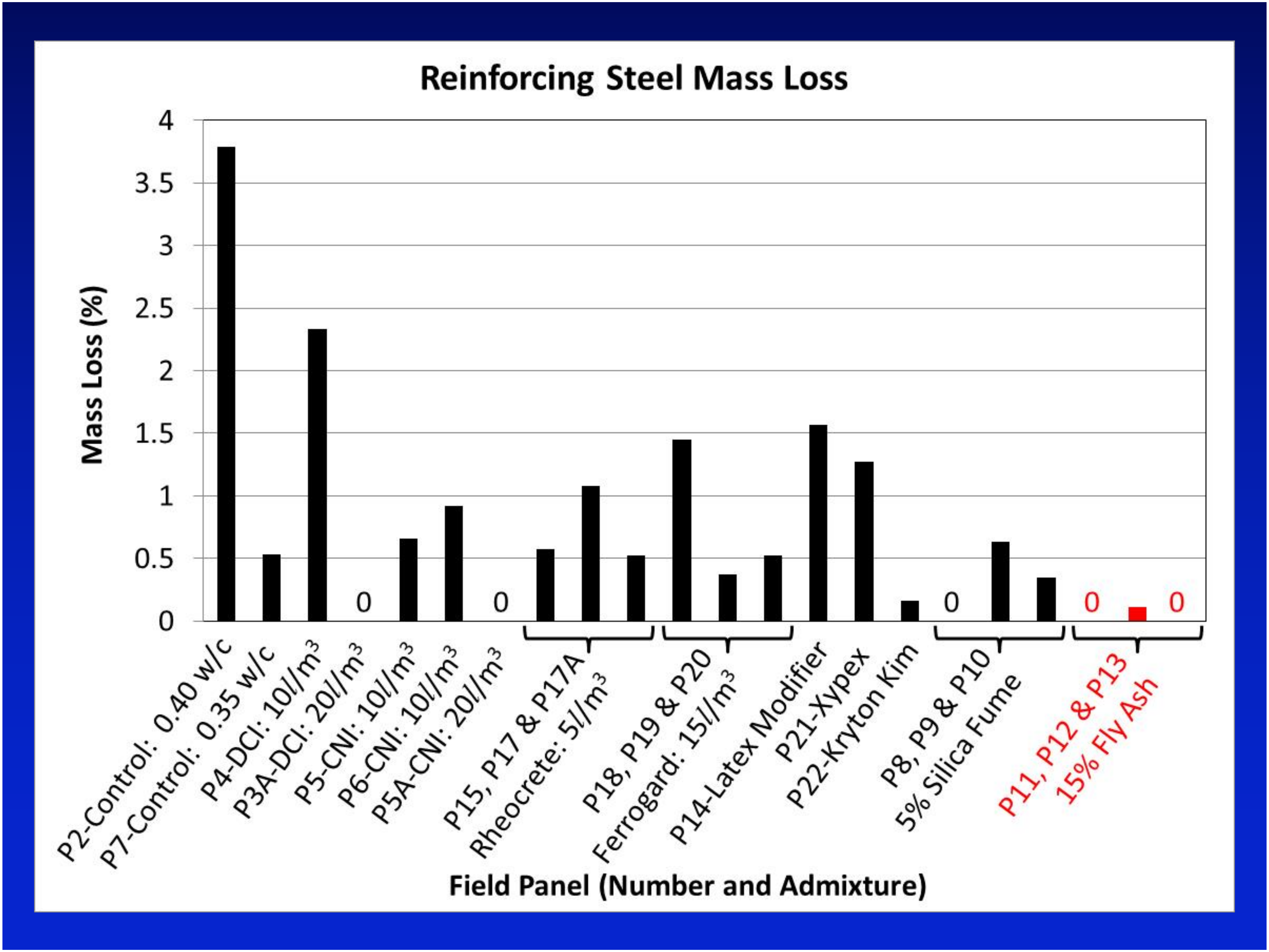
Field Panel (Number and Admixture)



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P4-DCI: 10l/m3
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P5-CNI: 10l/m3
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P15, P17 & P17A
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5% Silica Fume
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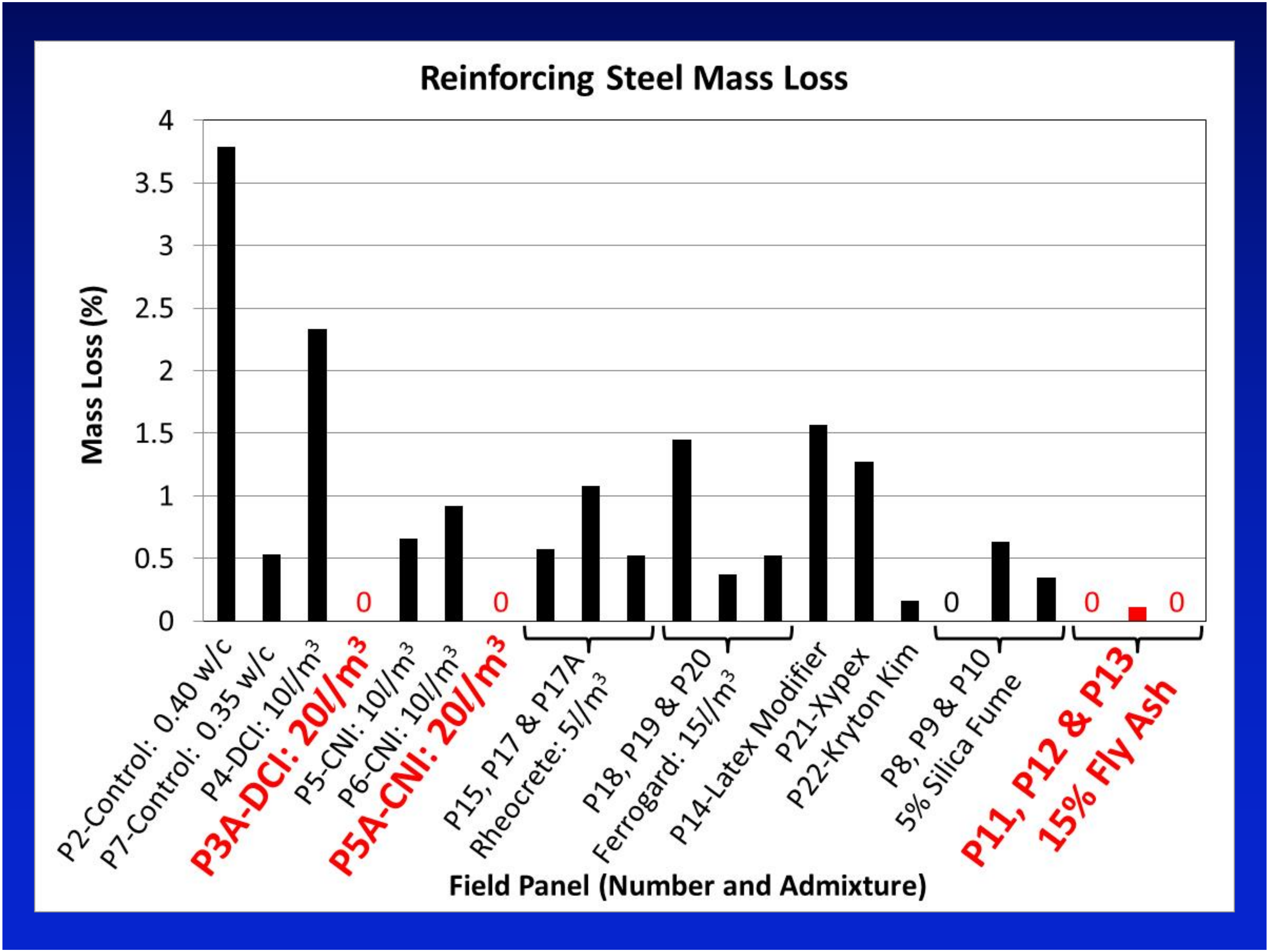
Field Panel (Number and Admixture)



Reinforcing Steel Mass Loss
Mass Loss (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0
0
0
0
P2-Control: 0.40 w/c
P7-Control: 0.35 w/c
P4-DCI: 10l/m3
P3A-DCI: 20l/m3
P5-CNI: 10l/m3
P6-CNI: 10l/m3
P5A-CNI: 20l/m3
P15, P17 & P17A
Rheocrete: 5l/m3
P18, P19 & P20
Ferrogard: 15l/m3
P14-Latex Modifier
P21-Xypex
P22-Kryton Kim
P8, P9 & P10
5% Silica Fume
P11, P12 & P13
15% Fly Ash
Field Panel (Number and Admixture)

Conclusions
Based on field specimens

- Control panel with w/c ratio of 0.35 performed better than control panels with w/c ratio of 0.40
- DCI and CNI both appear effective at 20 l/m^3 dosage. Results for 10 l/m^3 dosage not reliable.
- Rheocrete 222+ and FerroGard 901 provide varying performance results.
- Latex-modifier and Xypex Admix C-2000, showed poor performance.

Conclusions
Based on field specimens

- Panel with Kryton KIM showed minor corrosion and low half-cell readings after 9 years.
- Panels with 5% silica fume replacement showed inconsistent results – possibly due to inadequate distribution of silica fume during mixing
- Panels with 15% fly ash replacement showed good performance after 9 years.

Recommendations

- Use low w/c ratio mixtures
- Include fly ash replacement at 15% or greater
- Include DCI or CNI corrosion inhibitor at 20 l/m^3 or greater
- Possibly add Kryton KIM for additional protection

Kauai Hindu Temple
1000-year design life.

Final Design

- Use high Fly Ash concrete
- Use low cement and water content
- Use superplasticizers to increase slump
- Add superplasticizer, NOT WATER, at site
- All of the above reduce concrete shrinkage
- Monitor internal temperature of concrete to prevent thermal cracking
- Wet cure for 7 days or more
- Design for 3000psi concrete after 90 days

Application of burlap and moisture

Wet burlap covered with plastic sheet

Slow strength gain

Table 4 — Average compressive strength of concrete cylinders, MPa (psi)

Test age	Lower slab	Upper slab
3 days	6.0 (870)	7.3 (1065)
7 days	9.0 (1300)	10.9 (1580)
28 days	14.8 (2145)	17.5 (2540)
90 days	23.1 (3350)	27.6 (4000)


MANIVEL


Any Questions?