

PREDICTION OF CHLORIDE INGRESS INTO CONCRETE IN A MARINE ENVIRONMENT

Ian N. Robertson

University of Hawaii at Manoa

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Acknowledgements

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Division

Contributions by:
Ameron Hawaii
Hawaiian Cement

Graduate Students:
John Uno, Huiping Cheng, Joshua Ropert

Purpose of Research

- ❖ Evaluate chloride concentrations in reinforced concrete exposed to a marine environment
- ❖ Determine chloride ion penetration rates through concrete specimens made with Hawaiian aggregates
- ❖ Determine effectiveness of corrosion-inhibiting methods and admixtures in Hawaiian aggregate concrete
- ❖ Compare actual results to computer software predictions for future design

Review of Corrosion Process

- ❖ Concrete provides a naturally high-alkaline environment (pH of 12-13)
- ❖ This creates a passive oxide layer that acts as a natural barrier for the steel
- ❖ The most common reduction of this passivity is due to chloride ingress (ACI Committee 222, 2001)

Previous Phases of Research

❖ Phase I:

- Field evaluations at various harbor piers on Oahu to evaluate effectiveness of corrosion-inhibiting methods and admixtures

Research Report by:
Bola & Newton (2000)
<http://www.cee.hawaii.edu/>

Previous Phases of Research

❖ Phase II:

- Accelerated laboratory testing to evaluate the effectiveness of proposed corrosion-inhibiting methods and admixtures

Research Reports by:

Pham & Newton (2001)

Kakuda, Robertson & Newton (2005)

Okunaga, Robertson & Newton (2005)

<http://www.cee.hawaii.edu/>

UH Structures Laboratory Basement



8 Corrosion Inhibitors
100 different concrete mixtures
656 Individual specimens

Typical ASTM G 109 Test Specimen

Previous Phases of Research

❖ Phase III:

- Initiation of comparison of corrosion-inhibiting methods under field conditions
- Constructed and placed 25 reinforced concrete panels at Pier 38, Honolulu Harbor
- Panels installed between July 2002 to July 2003

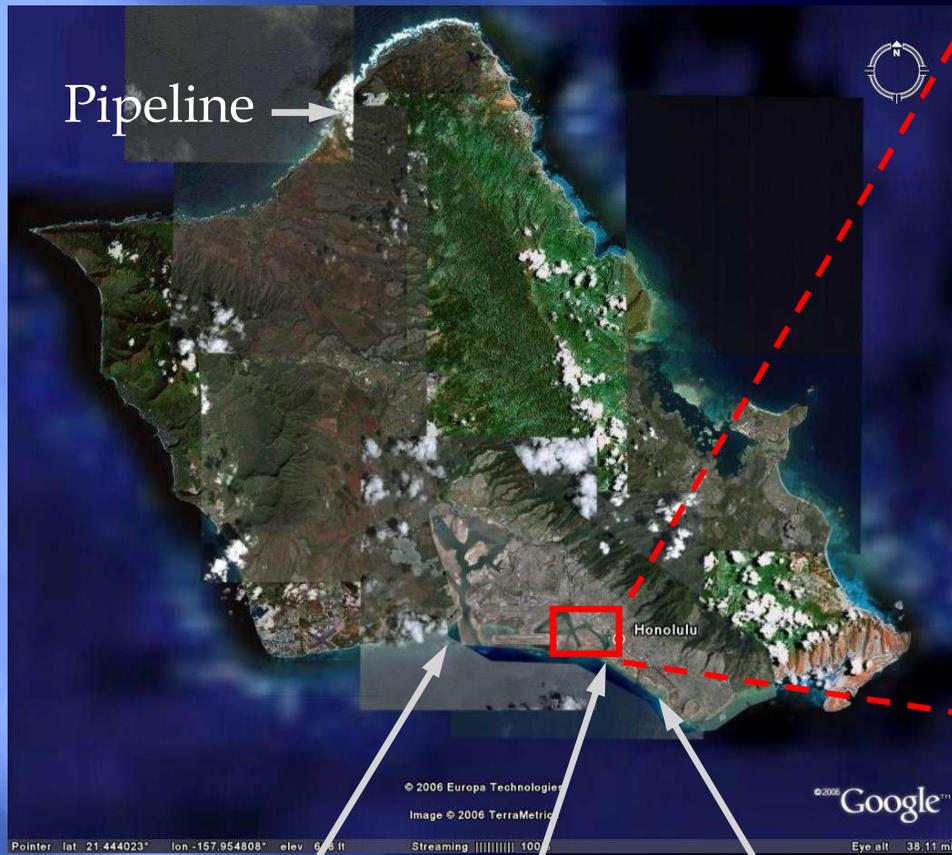
Research Reports by:

Uno, Robertson & Newtonson (2004)

Cheng & Robertson (2006)

Ropert & Robertson (2012)

<http://www.cee.hawaii.edu/>



Pipeline →

Honolulu

© 2006 Europa Technologies
Image © 2006 TerraMetric

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Pointer lat: 21.444023° lon: -157.954808° elev: 633 ft Streaming 100% Eye alt: 38.11 mi

Pearl Harbor

Honolulu Harbor

Waikiki Beach

Oahu, Hawaii



Kahala Island
Mokuueo Island
Mokuaea Island
Sand Island

Honolulu

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Pointer lat: 21.312876° lon: -157.876632° elev: 4 ft Streaming 100% Eye alt: 19.373 ft



Field Specimens

© 2006 Europa Technologies

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Admixtures in Field Panels

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



Admixtures in Field Panels

❖ **DAREX Corrosion Inhibitor (DCI)**

❖ **Rheocrete CNI**

❖ **Rheocrete 222+**

❖ **FerroGard 901**

❖ **Xypex Admix C-2000**

❖ **Latex-Modifier**

❖ **Silica Fume**

❖ **Fly Ash**

❖ **Kryton KIM**

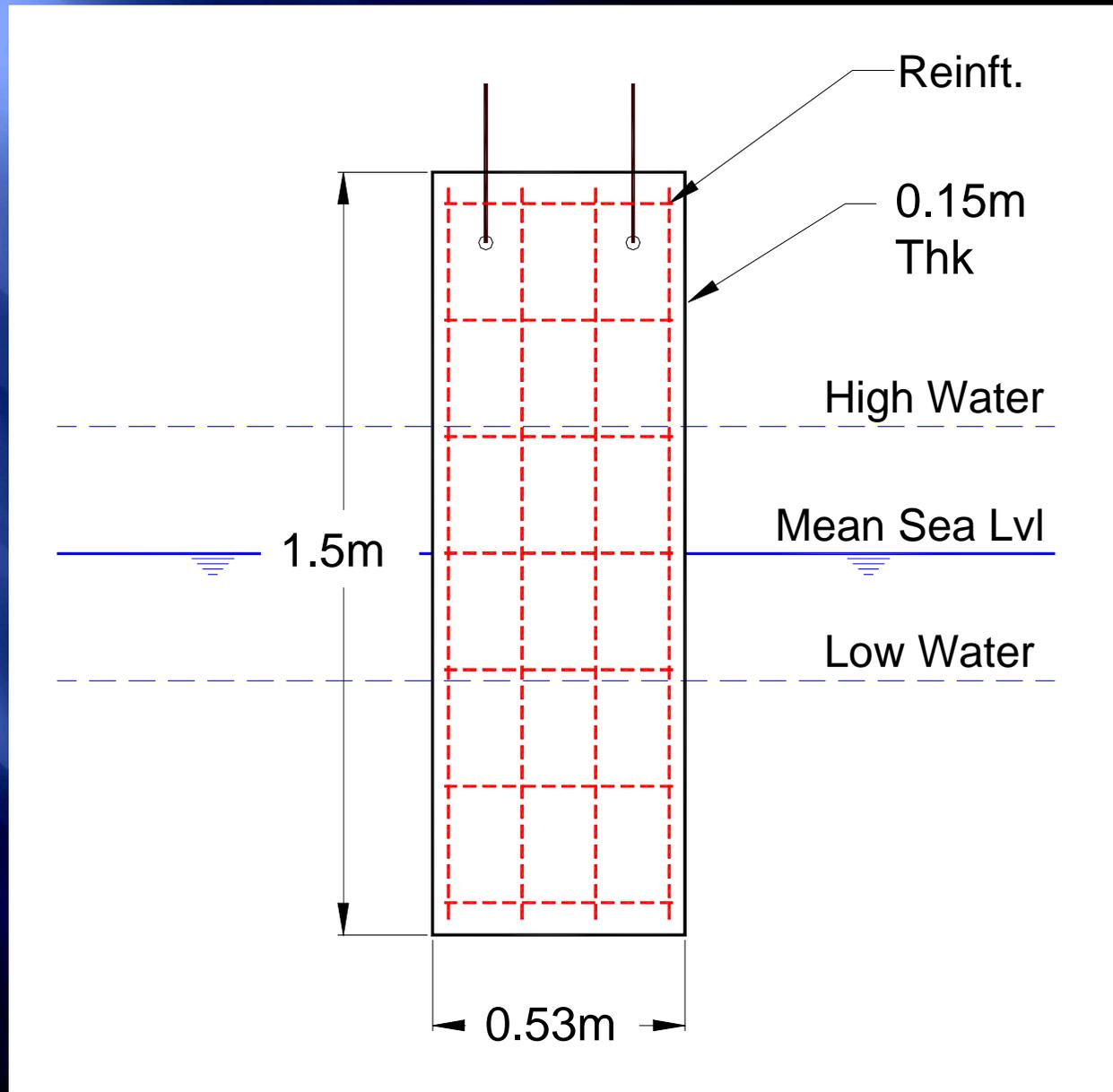


Field Panel Construction

Panel Reinforcement



Field Panel Placement



Field Panel Placement

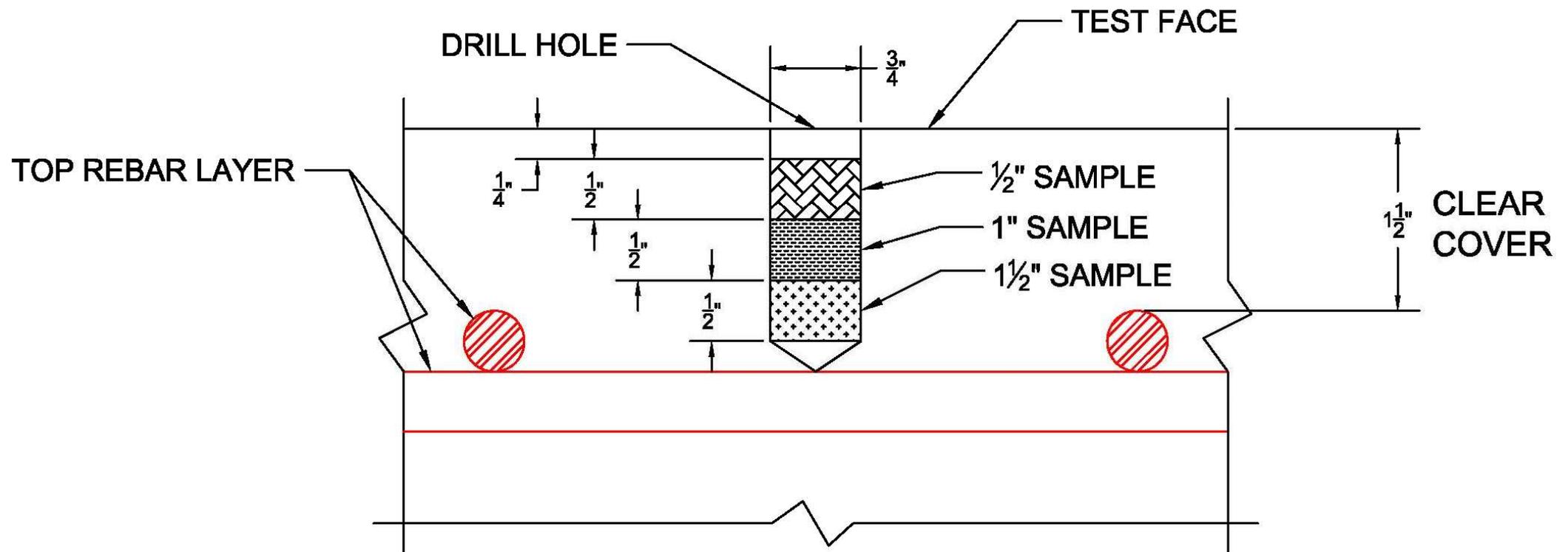


Chloride Concentration Samples

- ❖ Concrete samples were taken from three test locations on each field panel
 - Top – above the high tide mark
 - Middle – within tidal range
 - Bottom – fully submerged

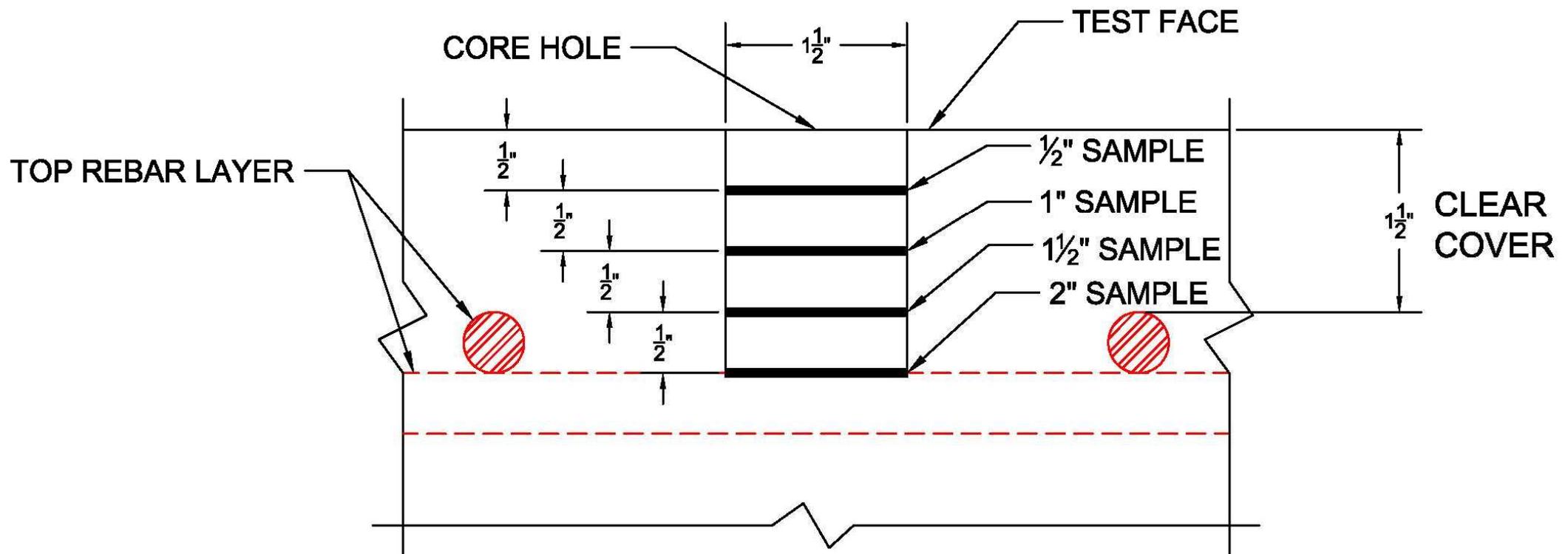
Chloride Concentration Samples

2004 concrete sampling method



Chloride Concentration Samples

2006 & 2008 concrete sampling method



Chloride Concentration Samples



Chloride Concentration Tests

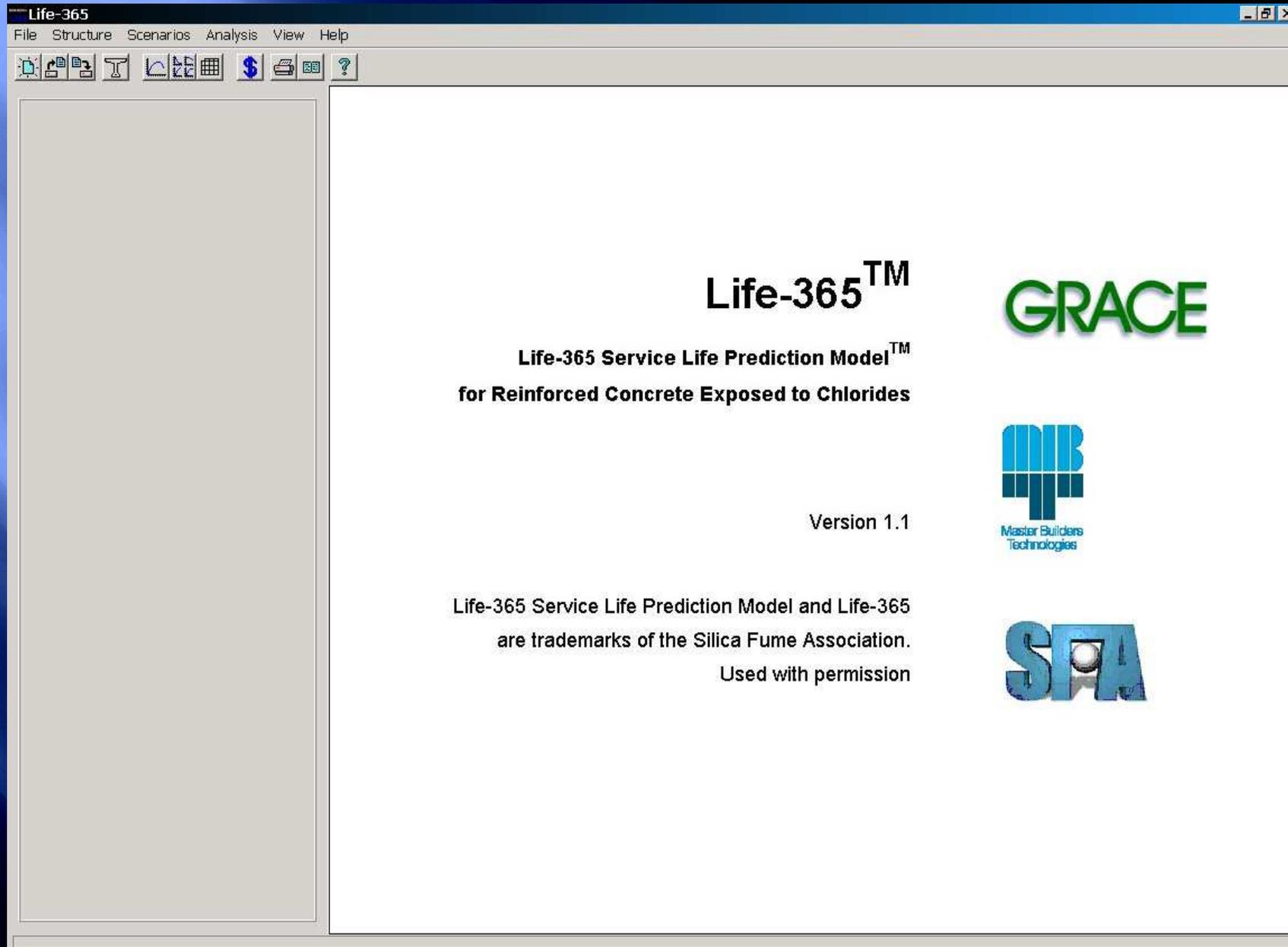


Chloride Concentration Tests

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



Life-365 Prediction Software



Life-365 Prediction Software

❖ Life-365 is a service life prediction software used to predict the service life and life-cycle costs of reinforced concrete that is exposed to chlorides.

Life-365 Prediction Software

❖ Under Consortium I, Version 1.0 was released in October 2000, and later revised as Version 1.1 in December 2001 to incorporate minor changes

❖ Consortium I contributors:

- W. R. Grace Construction Products
- Master Builders
- The Silica Fume Association

Life-365 Prediction Software

- ❖ The latest Version 2.1 was released January 2012
- ❖ Versions 2.0 to 2.1 were not used for this report as some options had been removed
 - No input to allow user to specify any age of chloride exposure
- ❖ Version 1.1 was therefore used for this report as options were included

Life-365 Prediction Software

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

Life-365 Mathematical Model

- ❖ Corrosion initiation assumes diffusion through the concrete is the dominant mechanism
- ❖ Fick's 2nd Law of Diffusion is used for Life-365 one -dimensional predictions:

$$\frac{dC}{dt} = D \cdot \frac{d^2C}{dx^2}$$

where: C = chloride content

D = apparent diffusion coefficient

x = depth (from the exposed surface)

t = time

Life-365 Mathematical Model

❖ The chloride diffusion coefficient, D , is a function of:

➤ Time

➤ Temperature

Life-365 Mathematical Model

❖ Time-dependent equation:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t} \right)^m$$

where: $D(t)$ = diffusion coefficient at time t

D_{ref} = diffusion coefficient at some reference time t_{ref}
(= 28 days in Life-365)

m = constant (depending on mix proportions)

Life-365 Mathematical Model

❖ The values of D_{ref} and m are based on the mix design parameters:

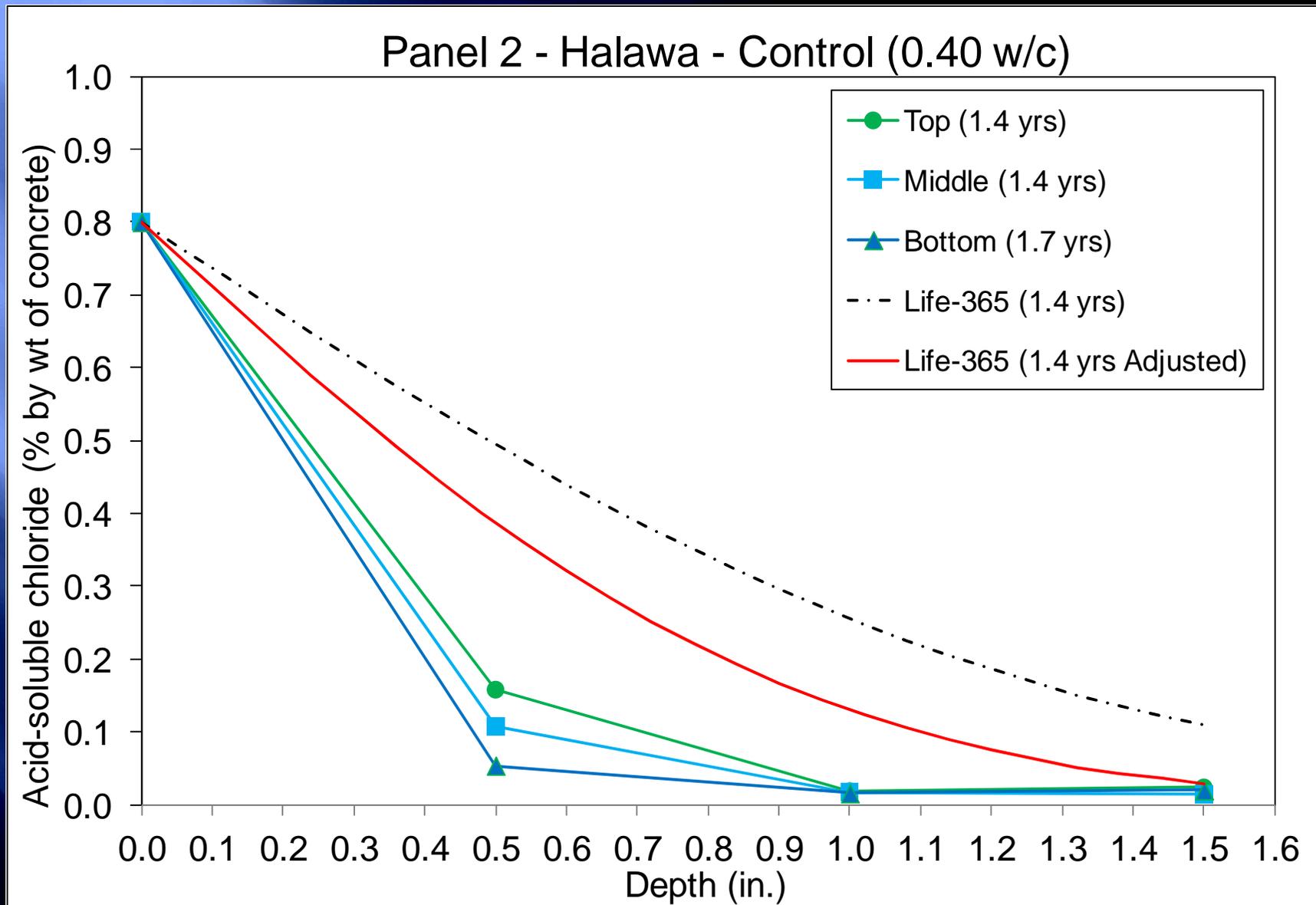
- Water-cementitious material ratio
- Type & proportion of cementitious materials (i.e. fly ash, silica fume, slag, etc.)

Chloride Concentrations with Life-365 Predictions

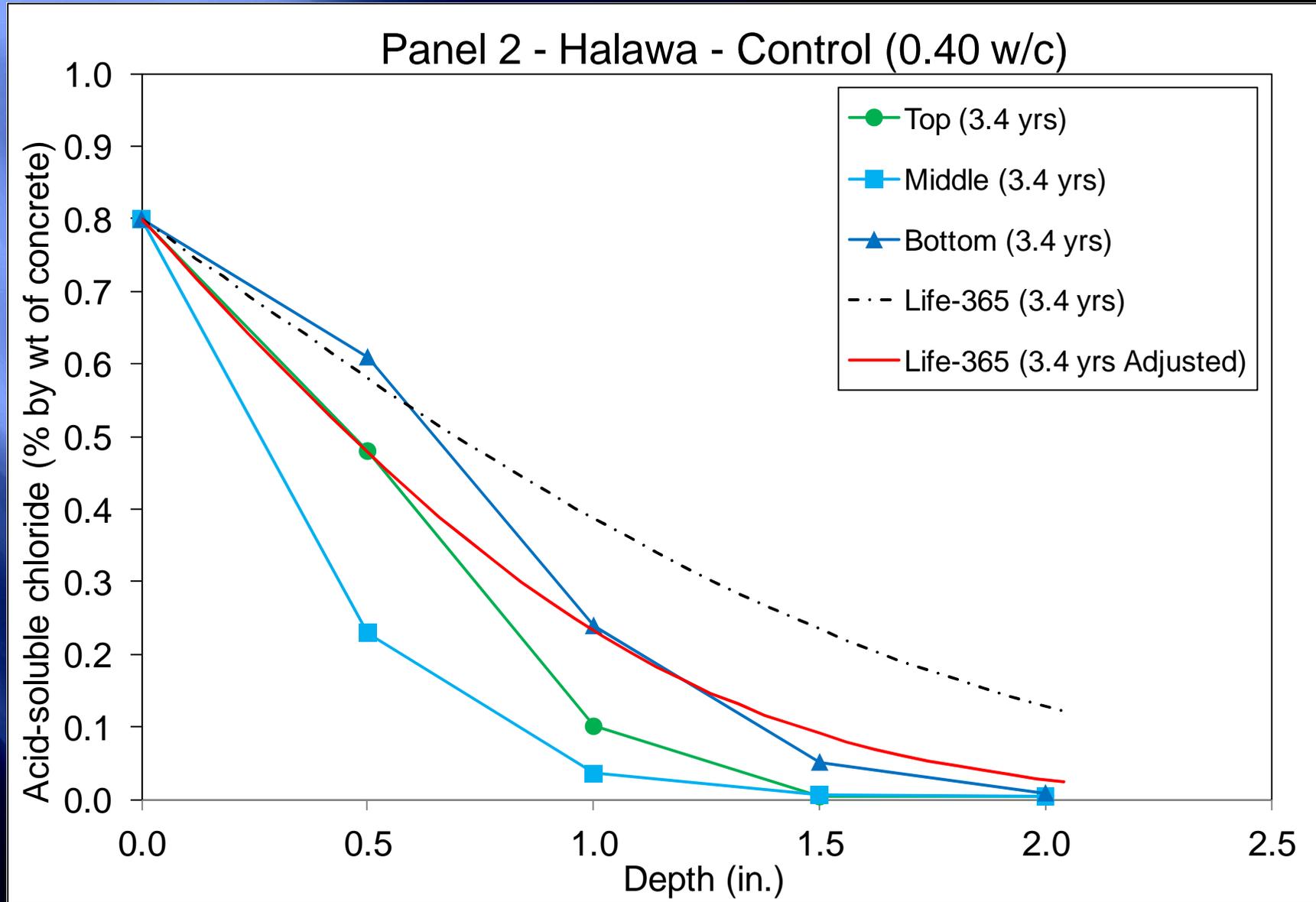
❖ Default and adjusted input values for Control Panels 1 and 2 (0.40 w/c ratio)

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

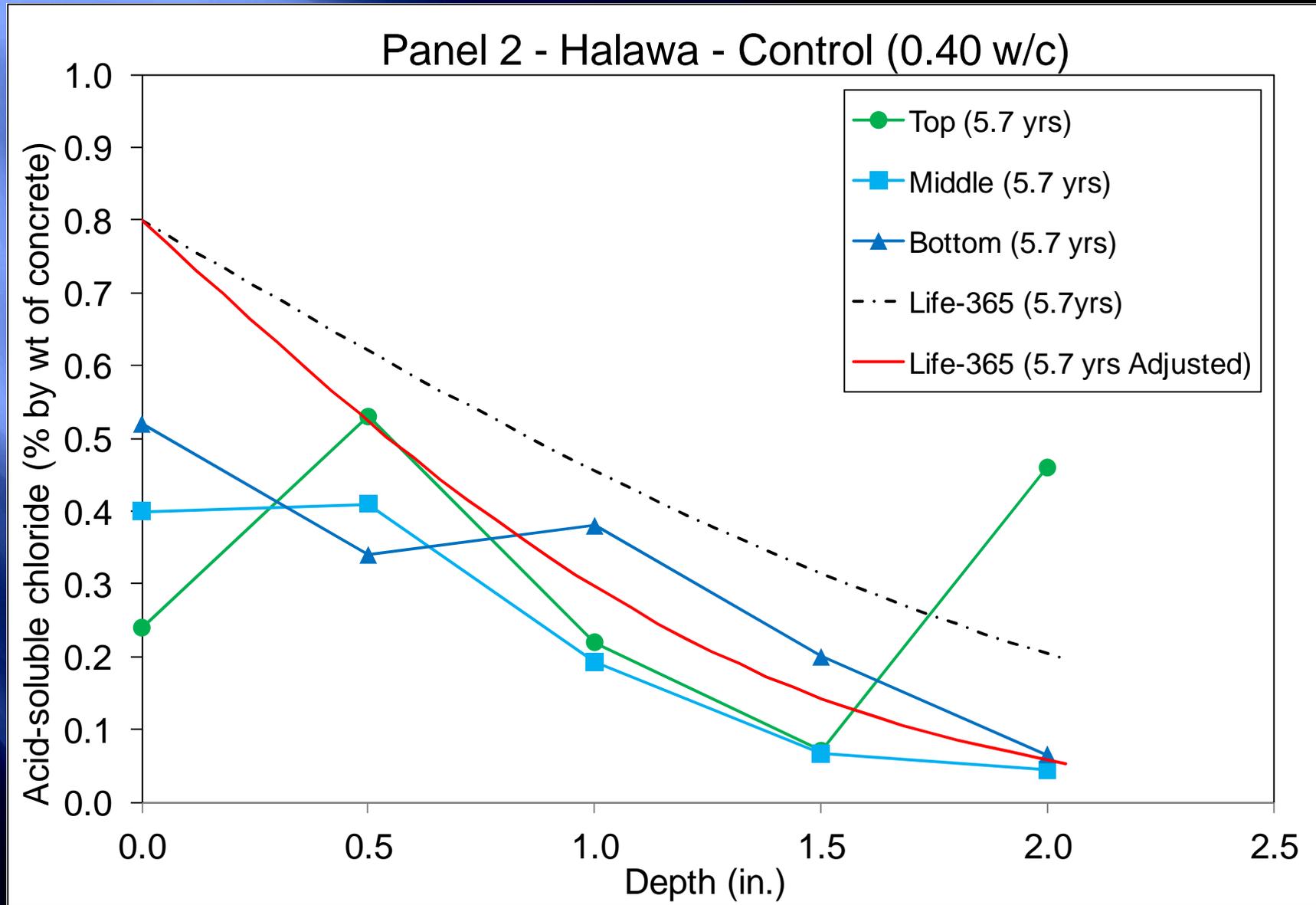
Chloride Concentrations with Life-365 Predictions



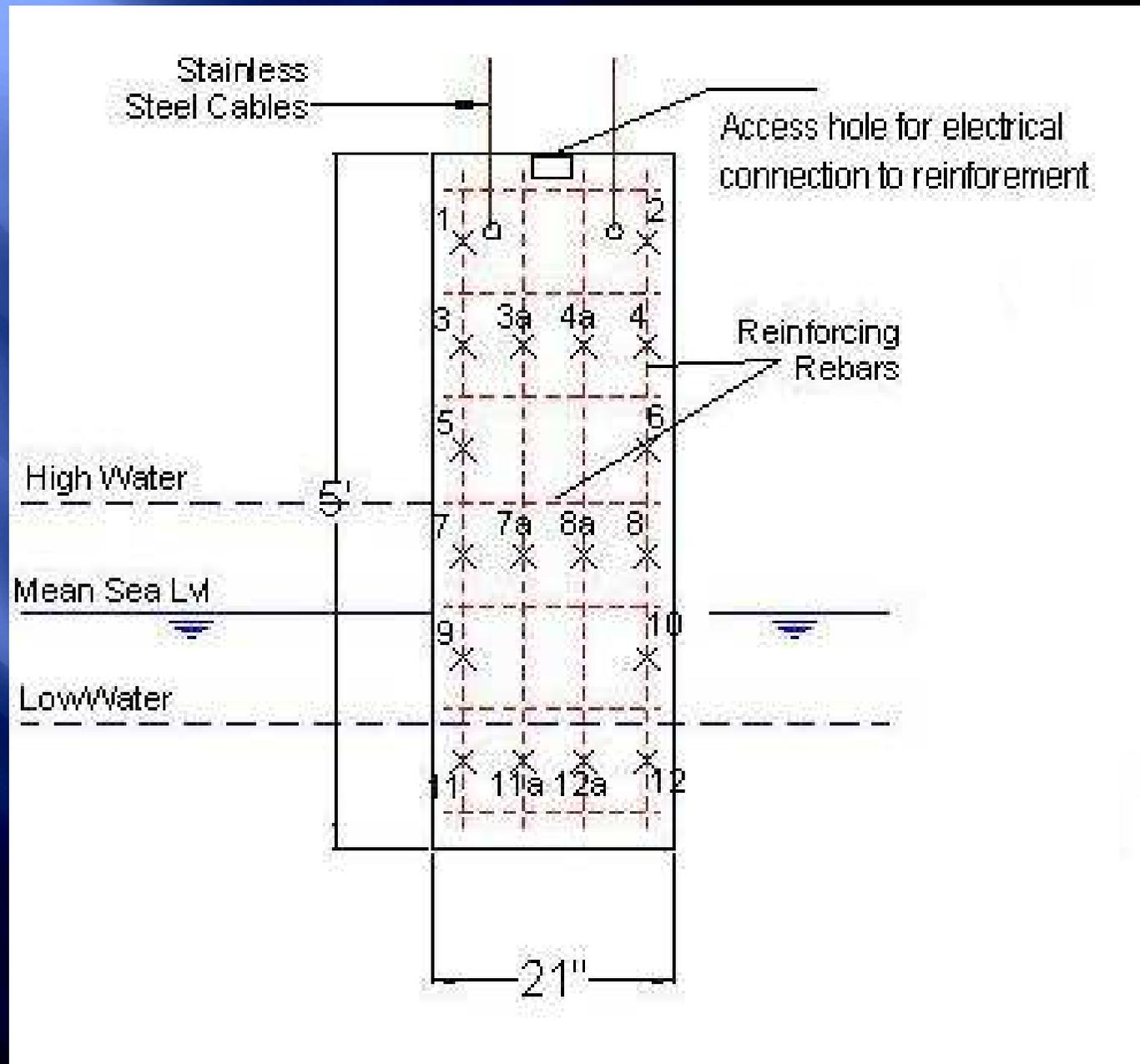
Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions

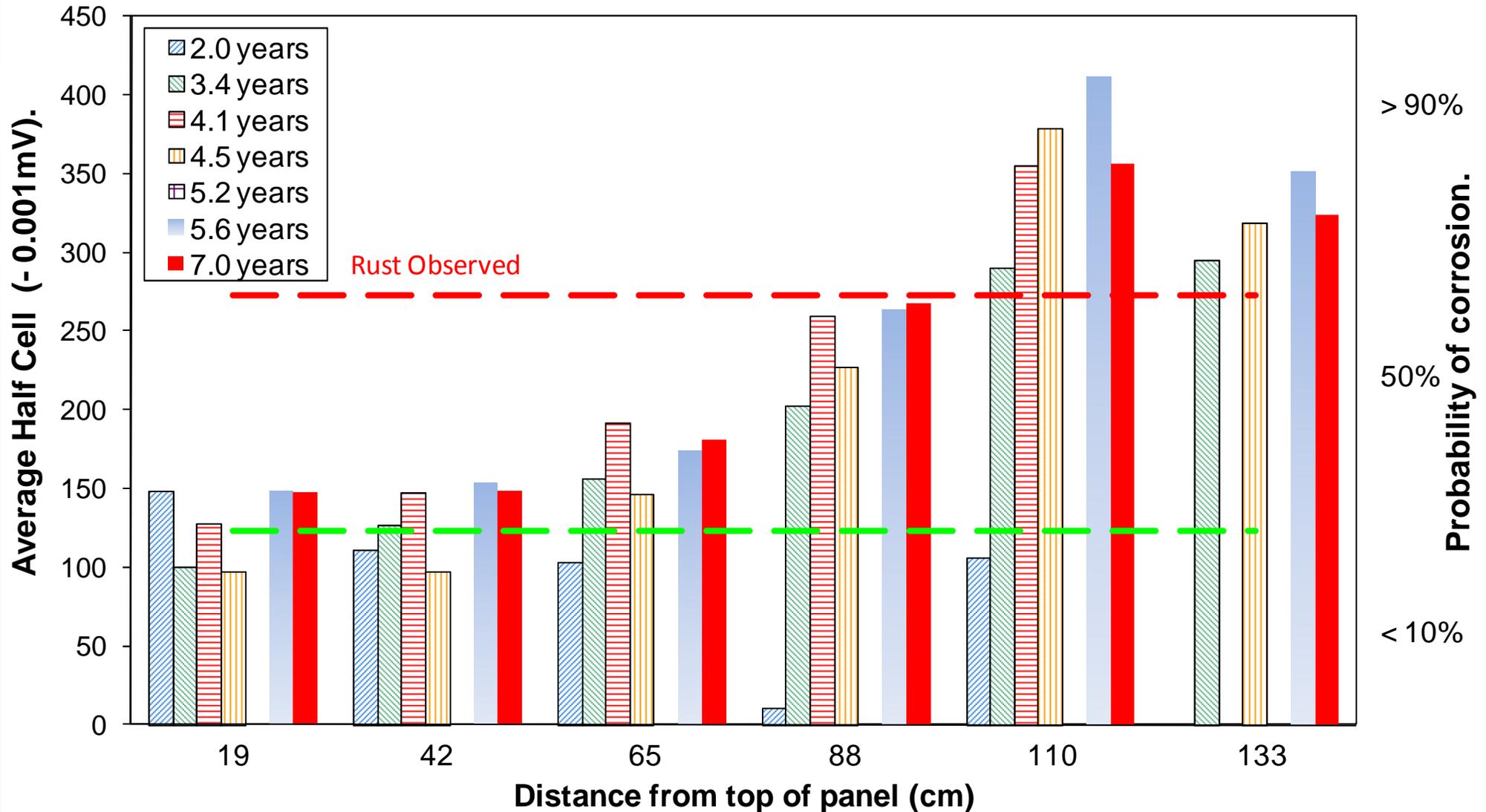


Half-cell Potential Tests



Halawa Control with 0.40 w/c ratio

Panel #2: Halawa Control with 0.40 w/c ratio



Halawa Control with 0.40 w/c ratio



Halawa Control with 0.40 w/c ratio

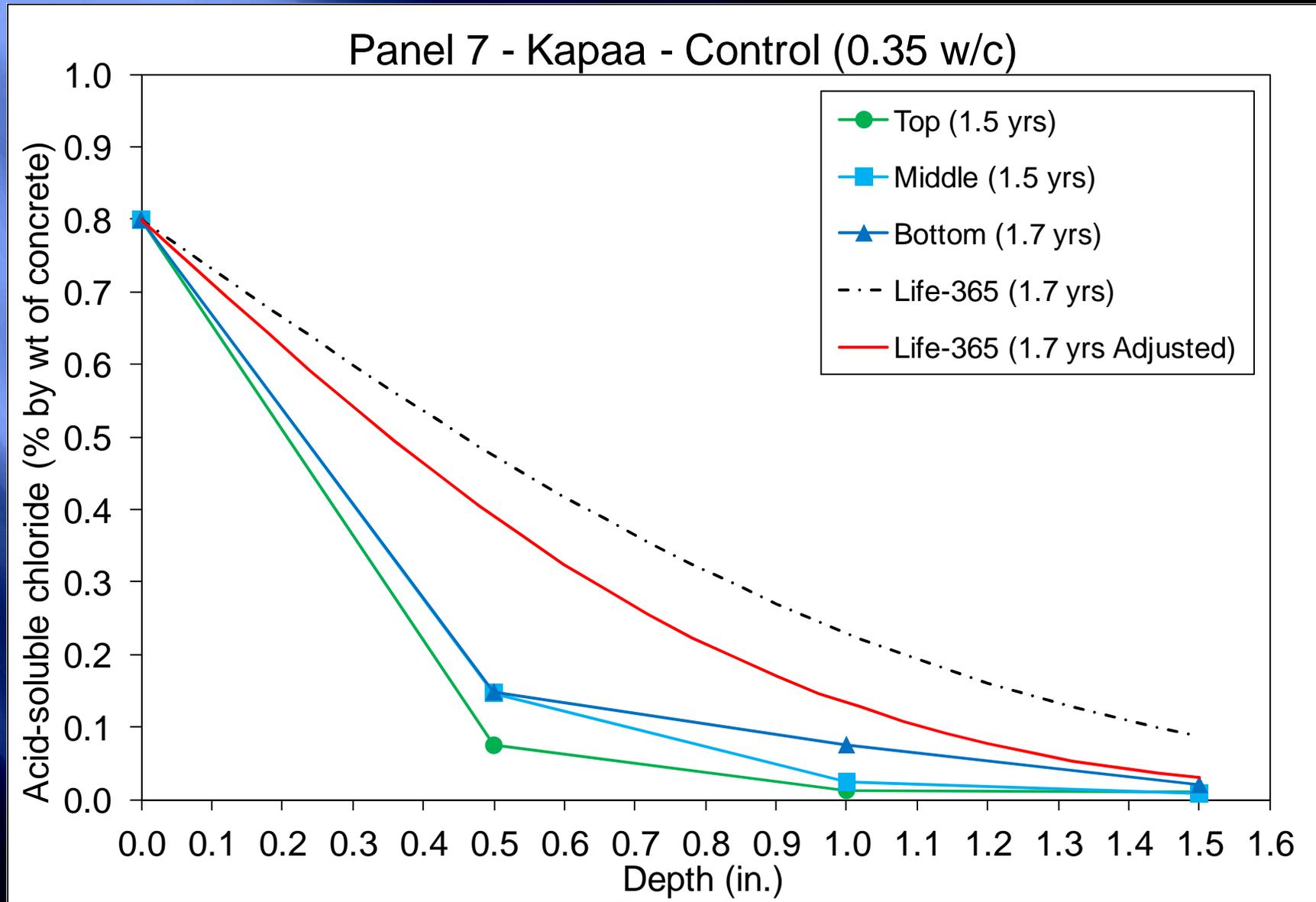


Chloride Concentrations with Life-365 Predictions

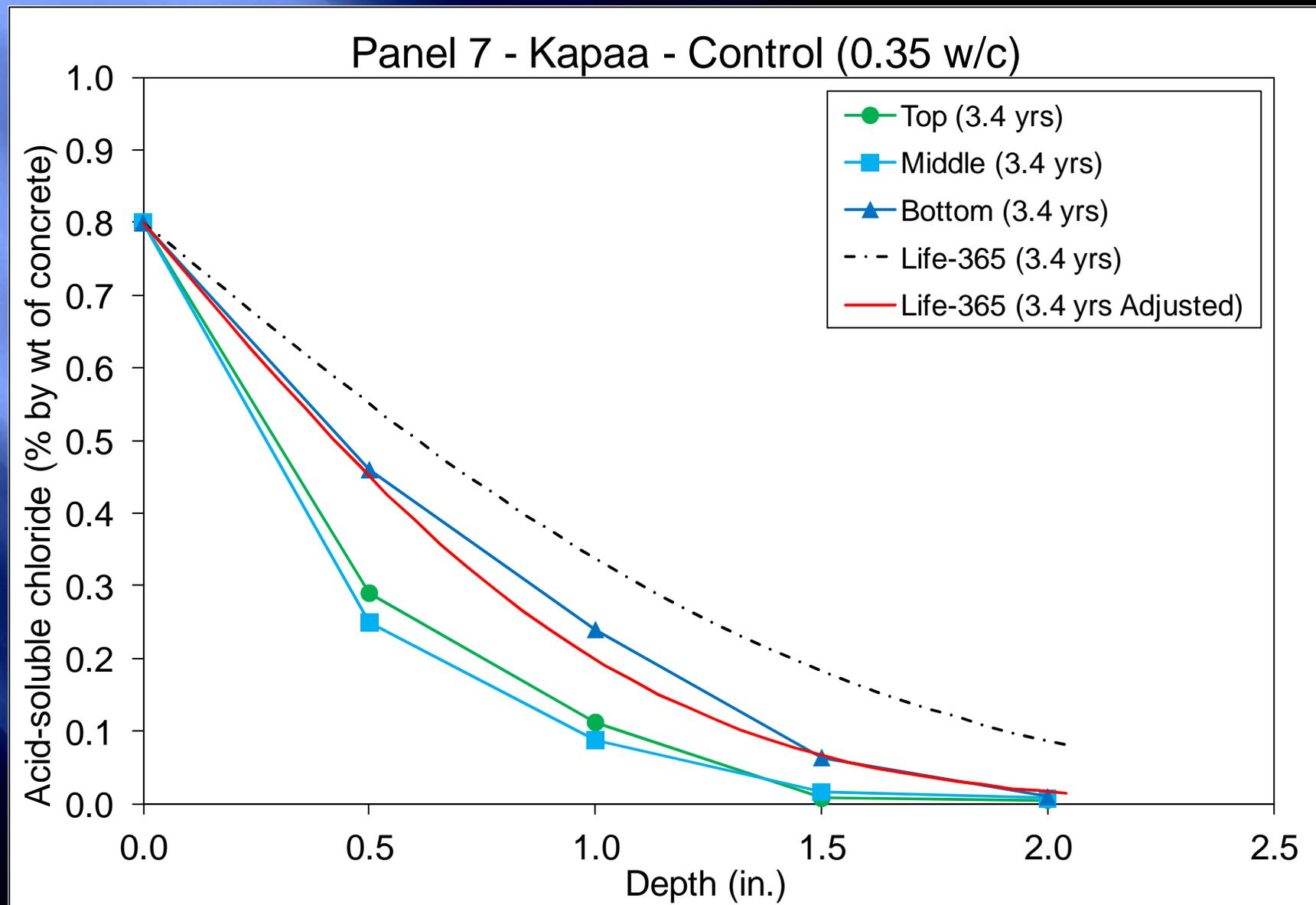
❖ Default and adjusted input values for Control Panel 7 (0.35 w/c ratio)

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

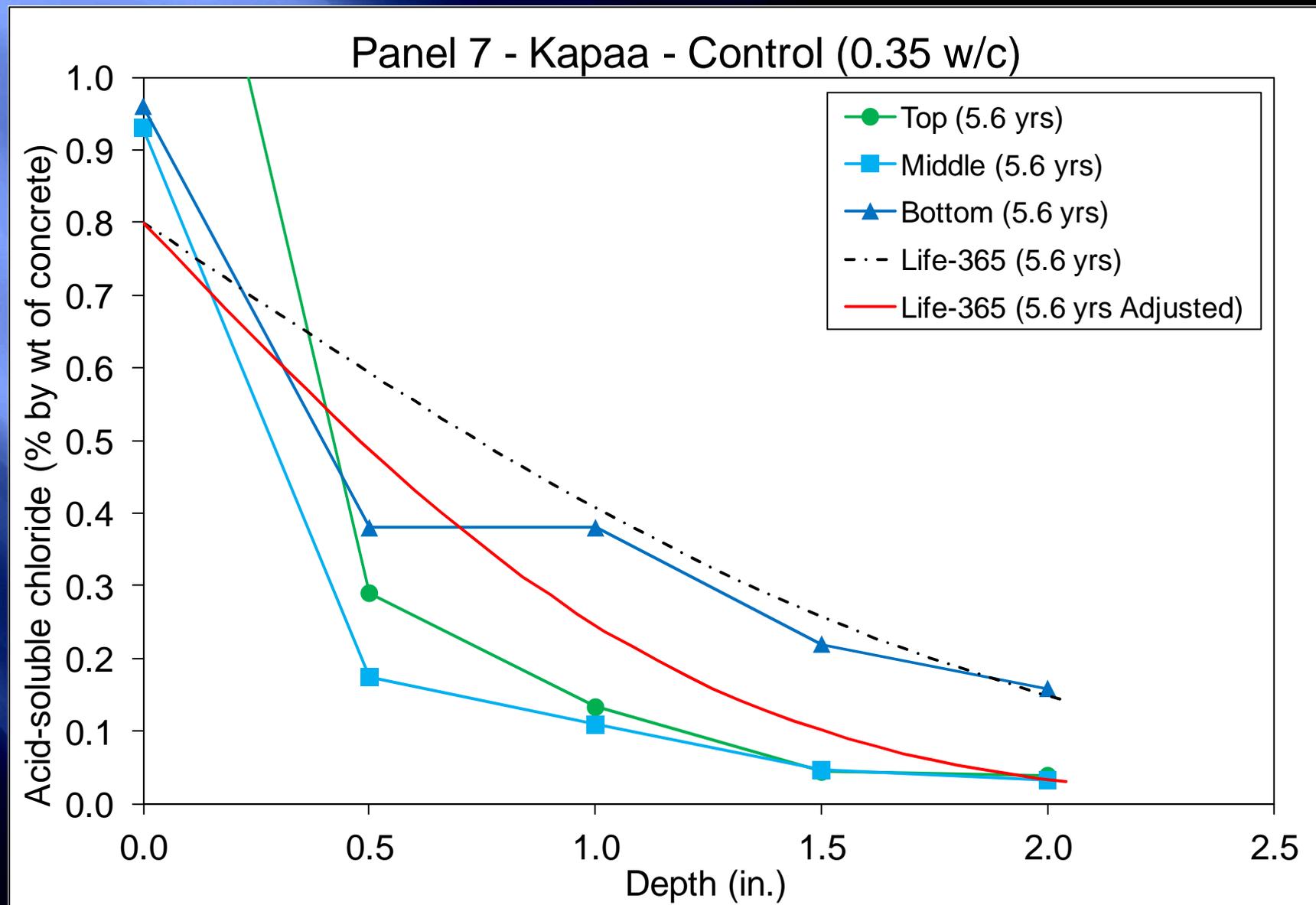
Chloride Concentrations with Life-365 Predictions



Chloride Concentrations with Life-365 Predictions

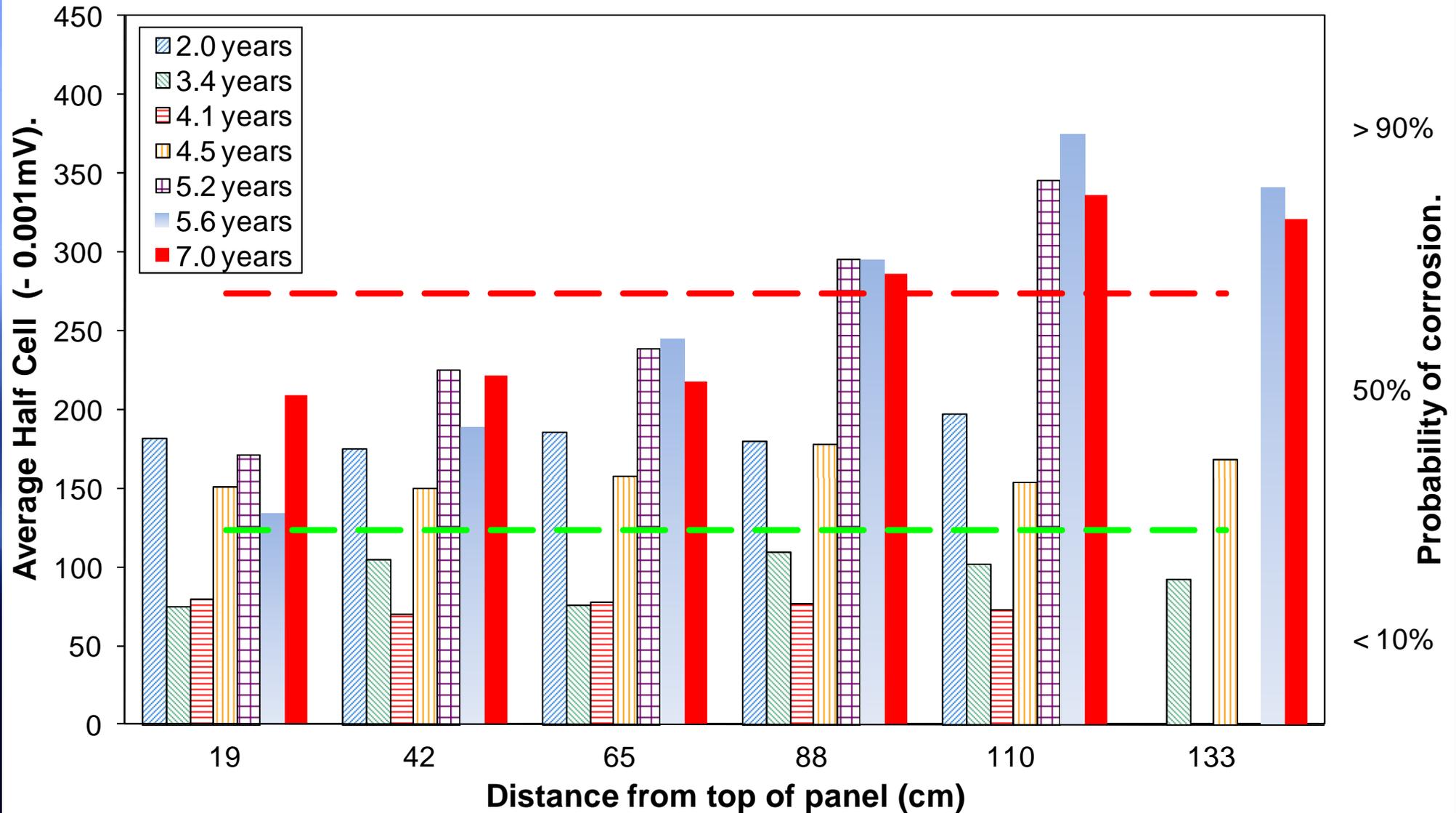


Chloride Concentrations with Life-365 Predictions



Kapaa Control with 0.35 w/c ratio

Panel #7: Kapaa Control with 0.35 w/c ratio



Kapaa Control with 0.35 w/c ratio

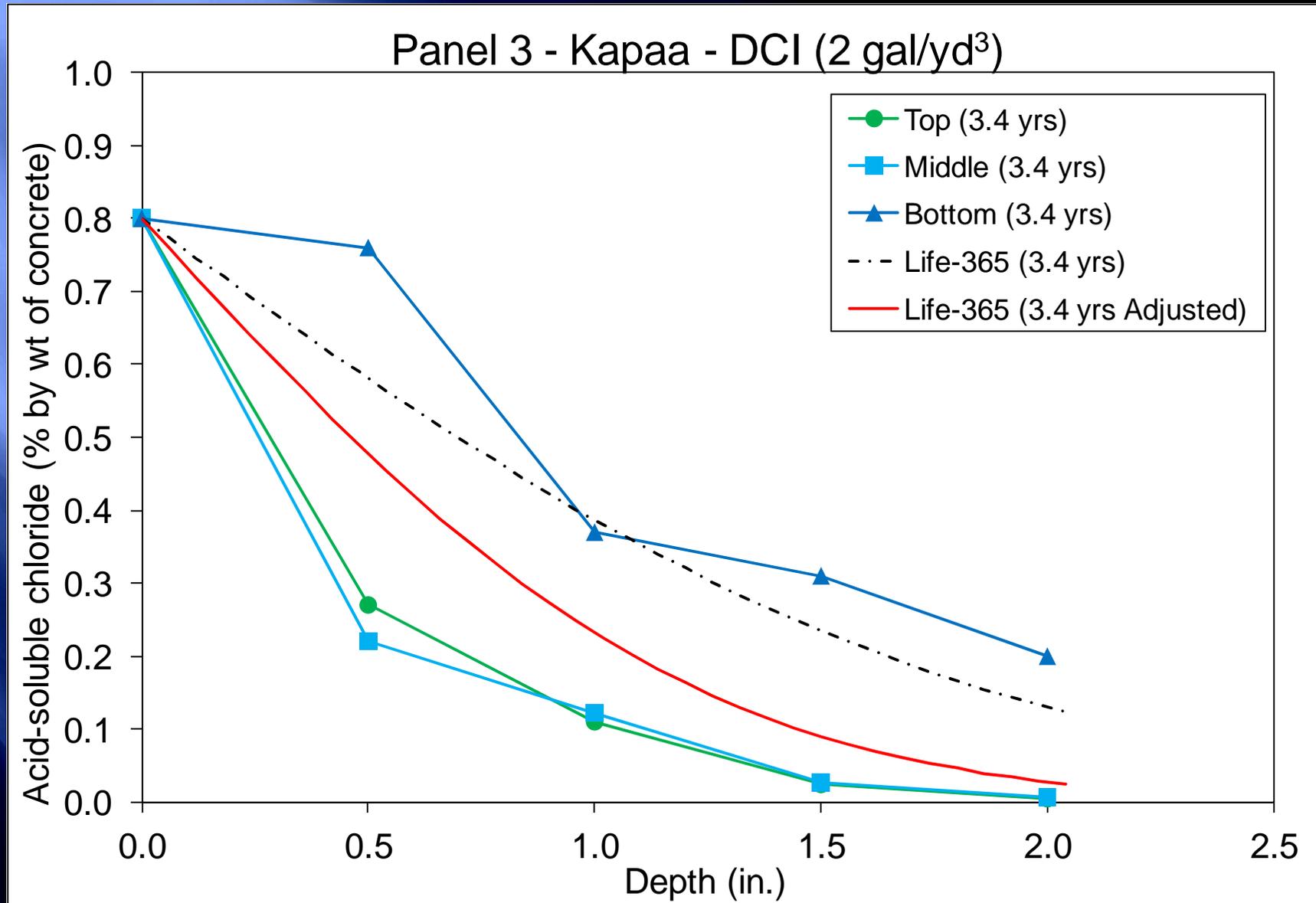


Chloride Concentrations with Life-365 Predictions

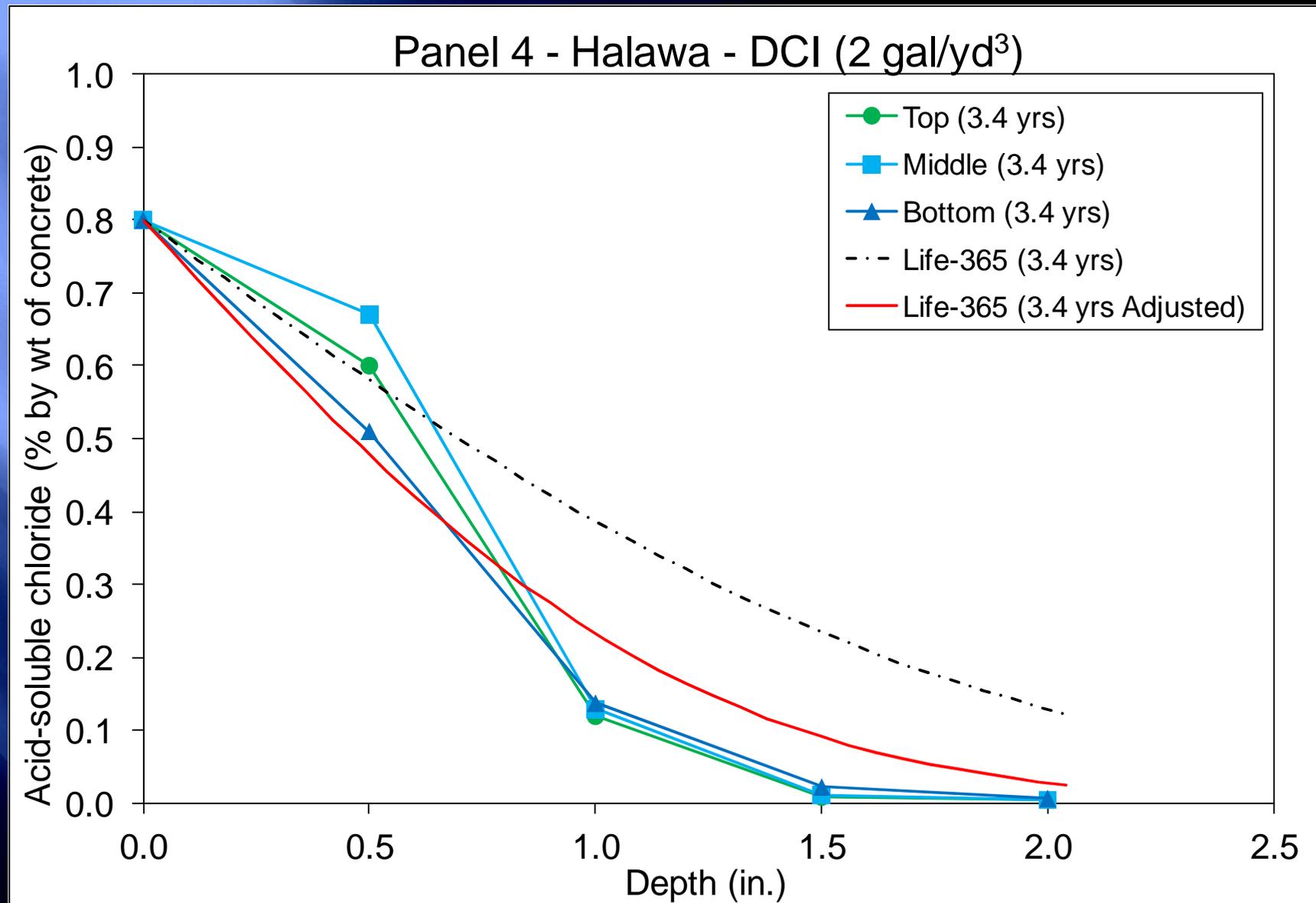
❖ Default and adjusted input values for DCI Panels (with $10\ell/m^3$ and $20\ell/m^3$)

	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

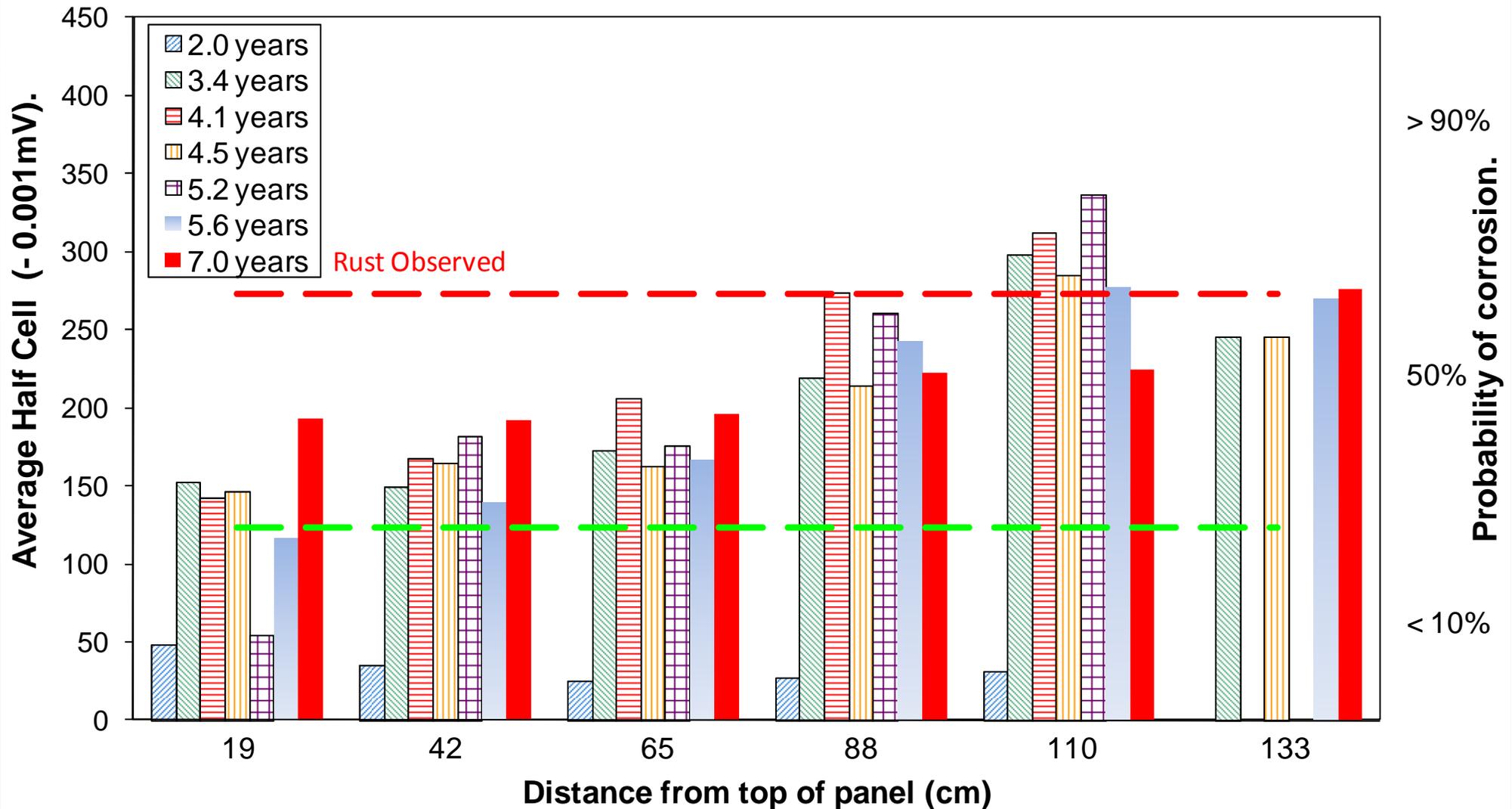


Chloride Concentrations with Life-365 Predictions

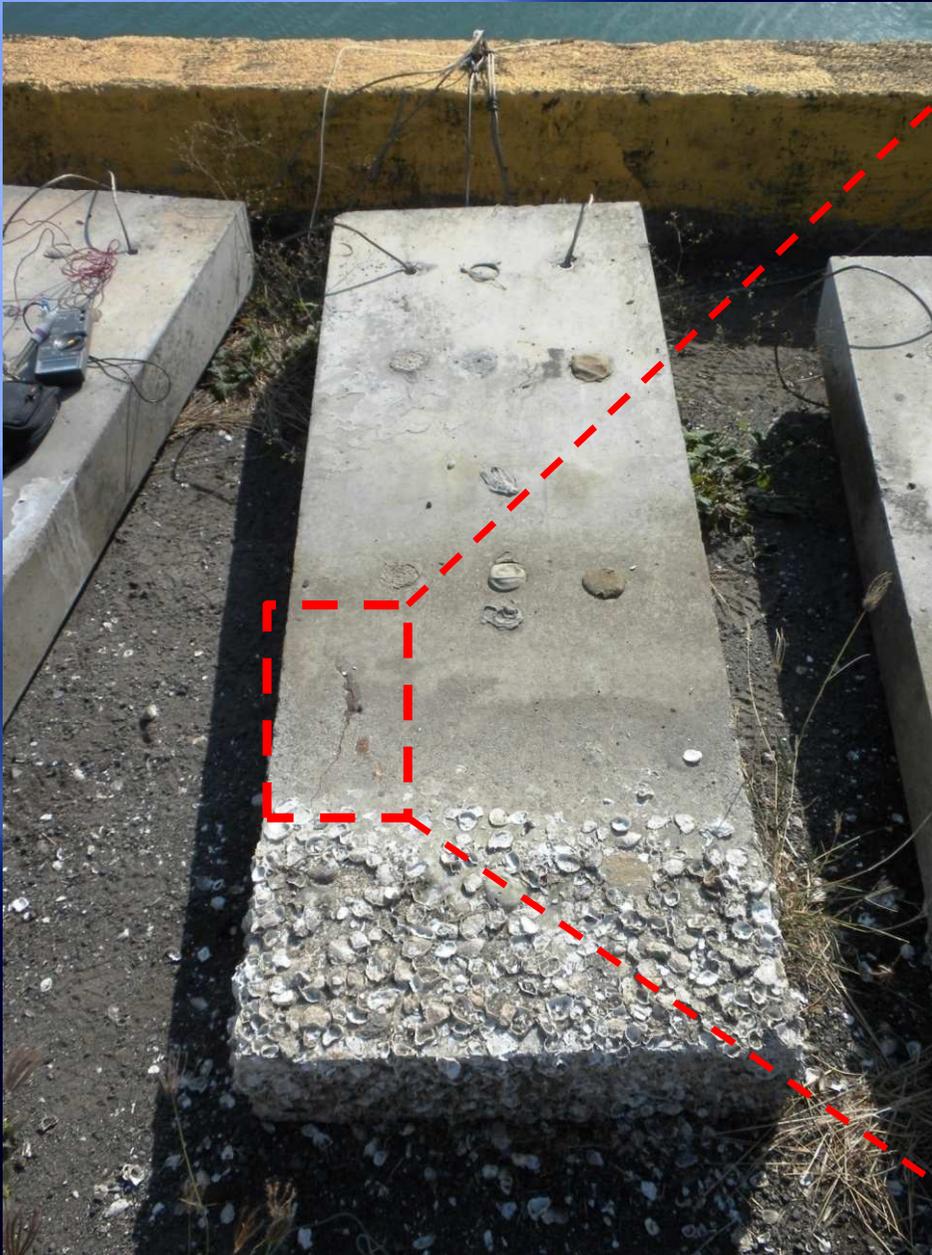


Halawa 0.40 w/c ratio w/10ℓ/m³ DCI

Panel #4: Halawa 0.40 w/c with DCI at 10ℓ/m³ (2 gal/cuyd)

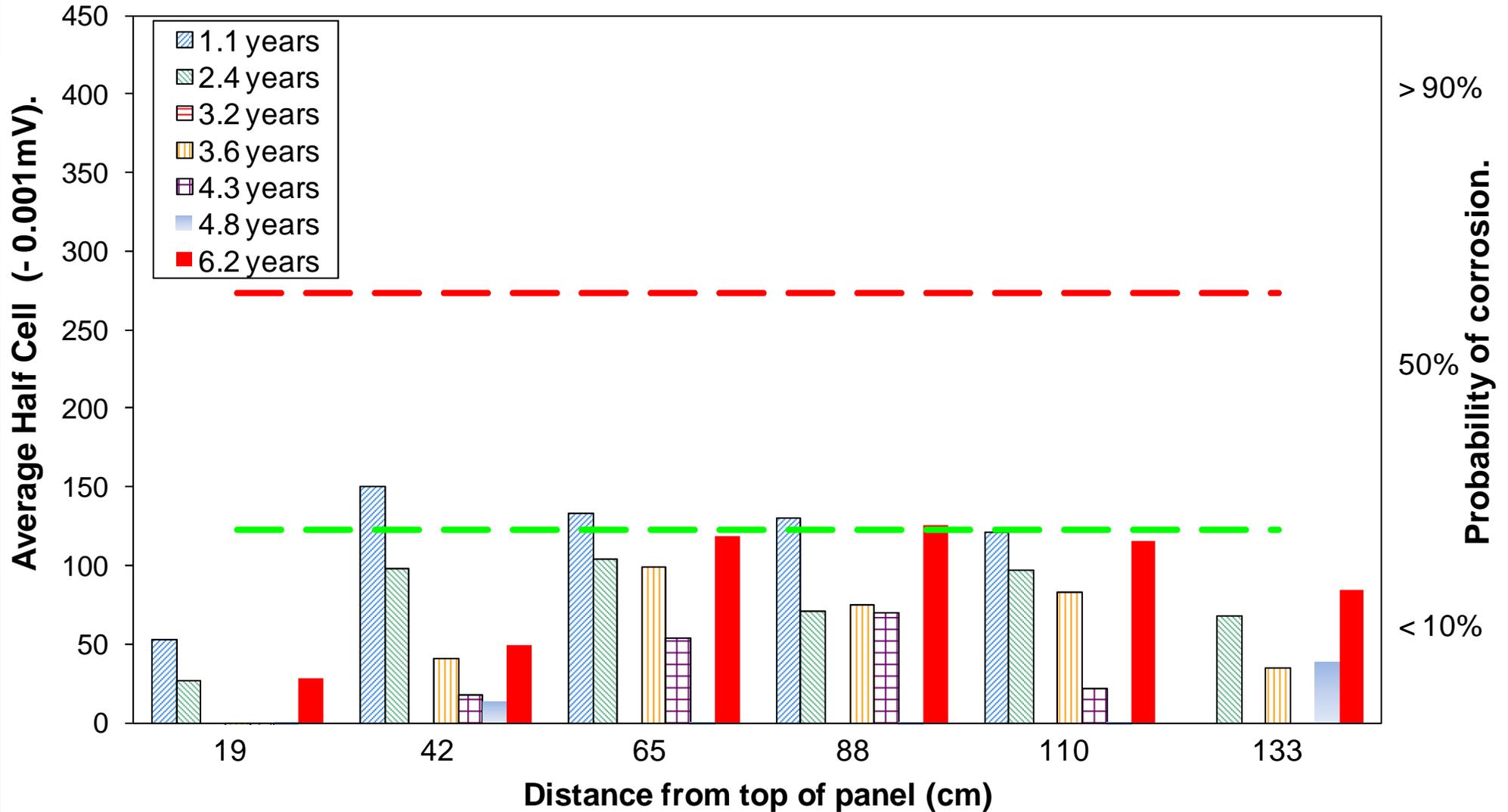


Halawa 0.40 w/c ratio w/10ℓ/m³ DCI



Kapaa 0.40 w/c ratio w/20ℓ/m³ DCI

Panel #3A: Kapaa 0.40 w/c with DCI at 20ℓ/m³ (4 gal/cuyd)



Kapaa 0.40 w/c ratio with $20\ell/m^3$ DCI

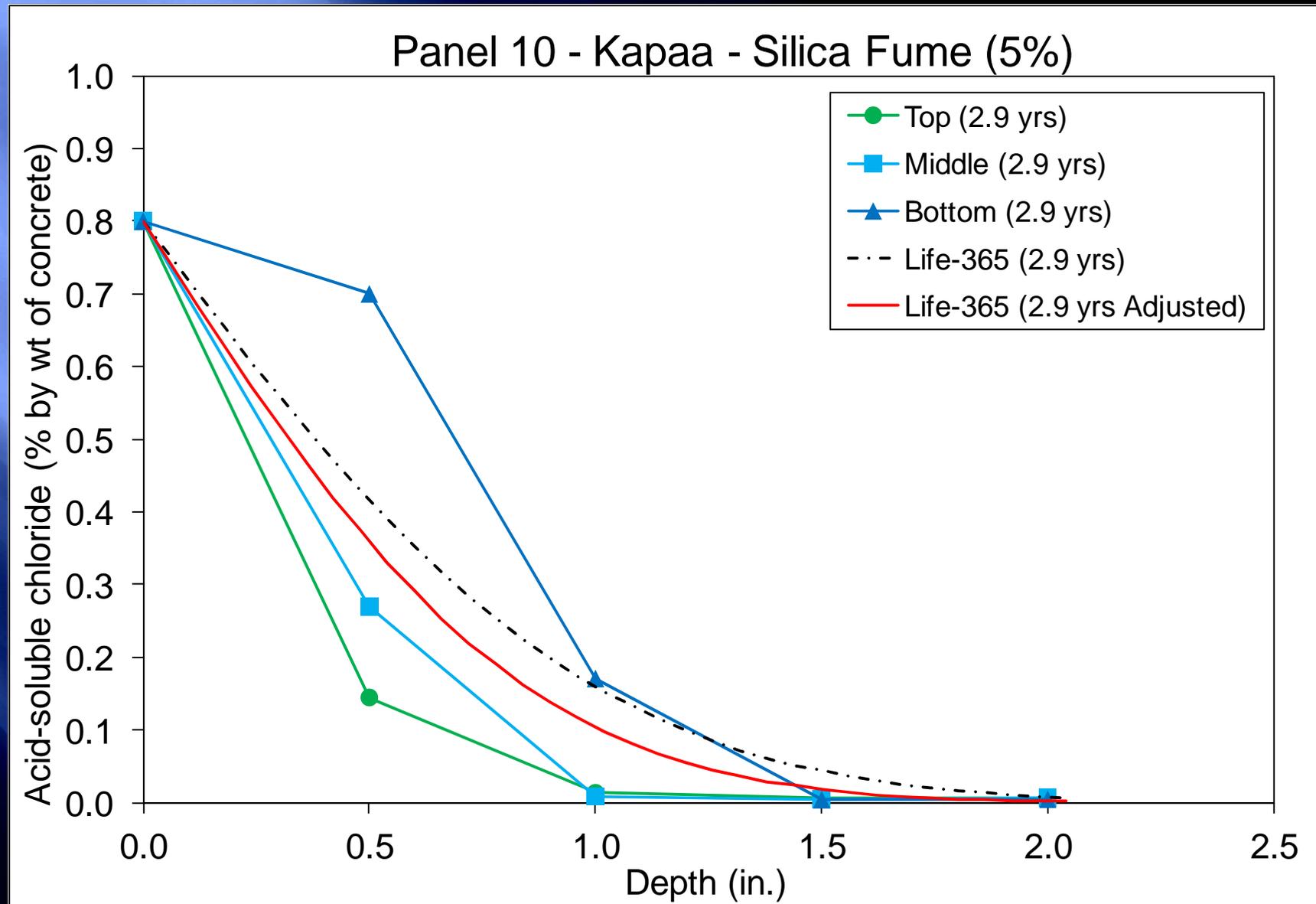


Chloride Concentrations with Life-365 Predictions

❖ Default and adjusted input values for Silica Fume Panels

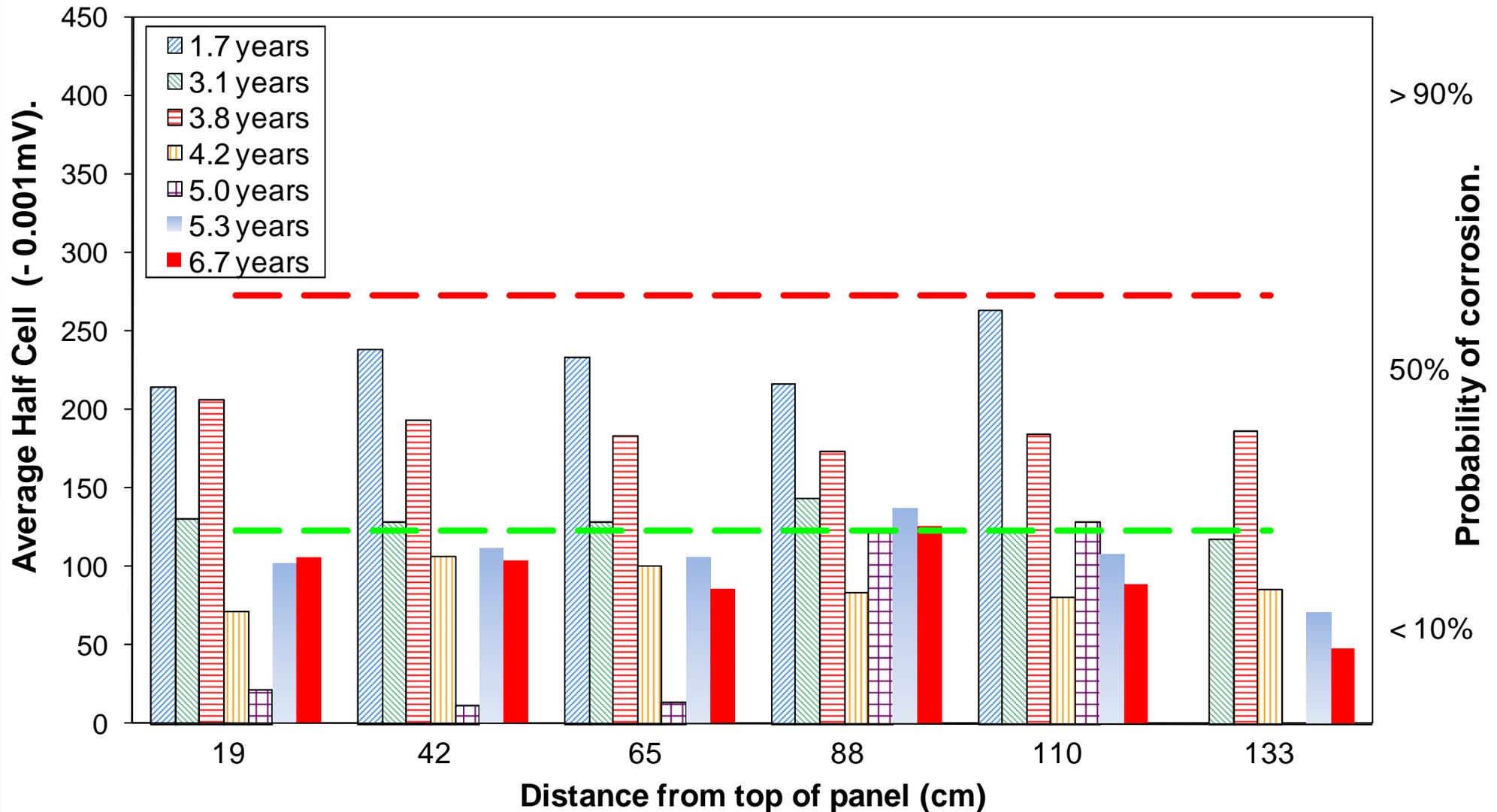
	Default values	Adjusted values
Diffusion coefficient	2.71E-12	2.50E-12
m	0.20	0.30
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



Kapaa 0.36 w/c; 5% Silica Fume

Panel #8: Kapaa 0.36 w/c with 5% Silica Fume (Master Builders)

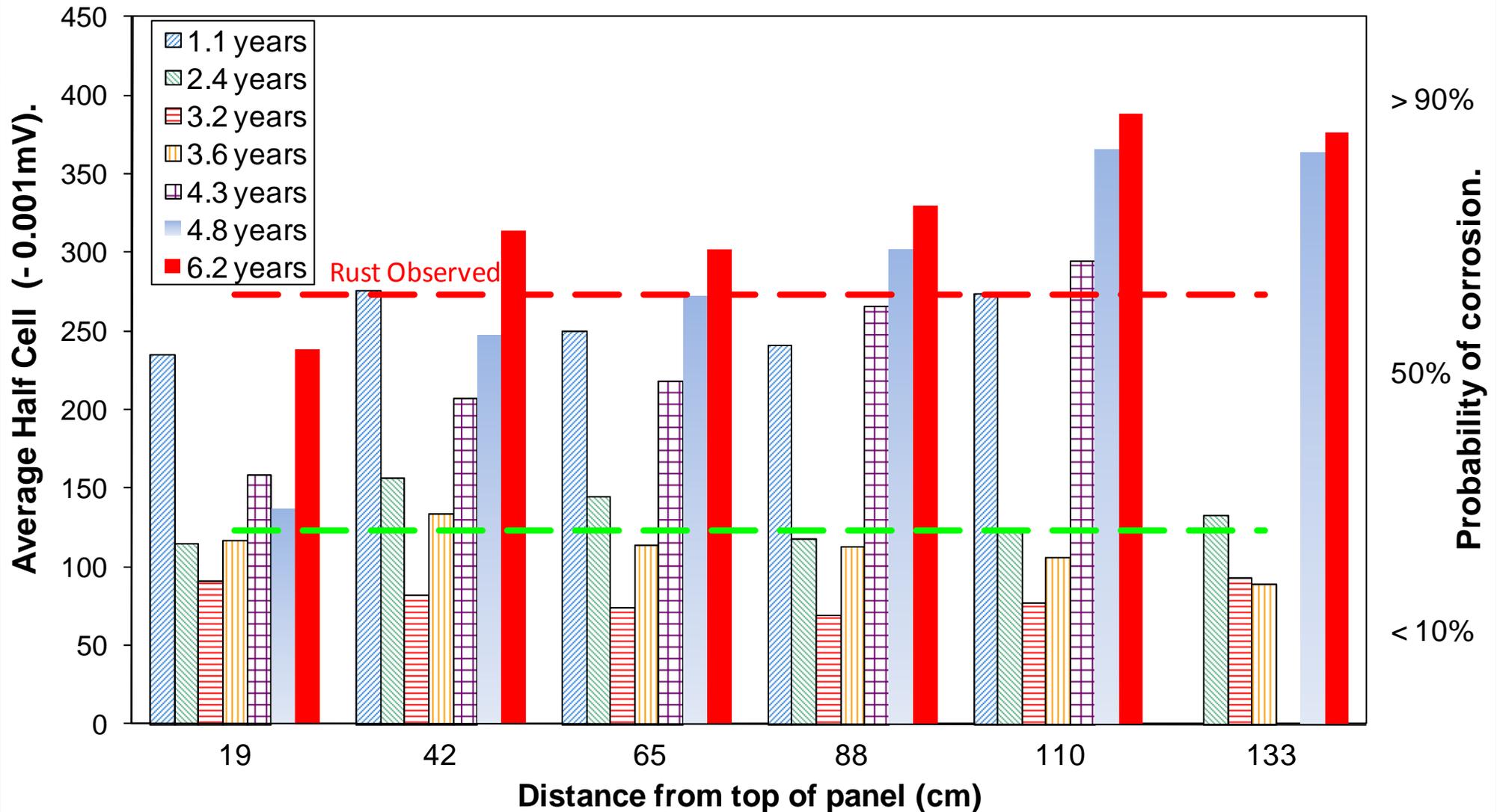


Караа 0.36 w/c; 5% Silica Fume



Kapaa 0.36 w/c; 5% Silica Fume

Panel #9: Kapaa 0.36 w/c with 5% Silica Fume (Master Builders)



Καπα 0.36 w/c; 5% Silica Fume

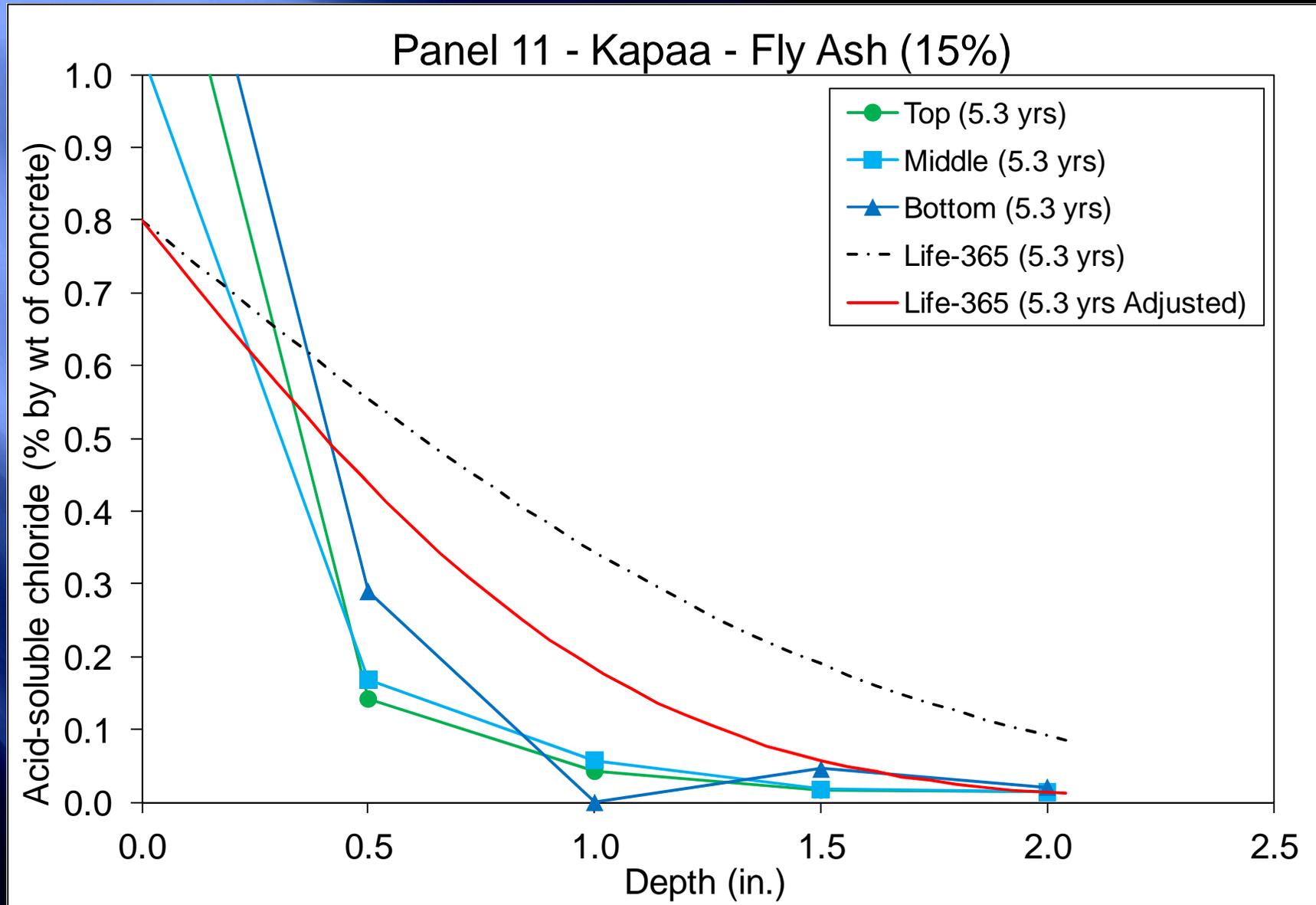


Chloride Concentrations with Life-365 Predictions

❖ Default and adjusted input values for Fly Ash Panels

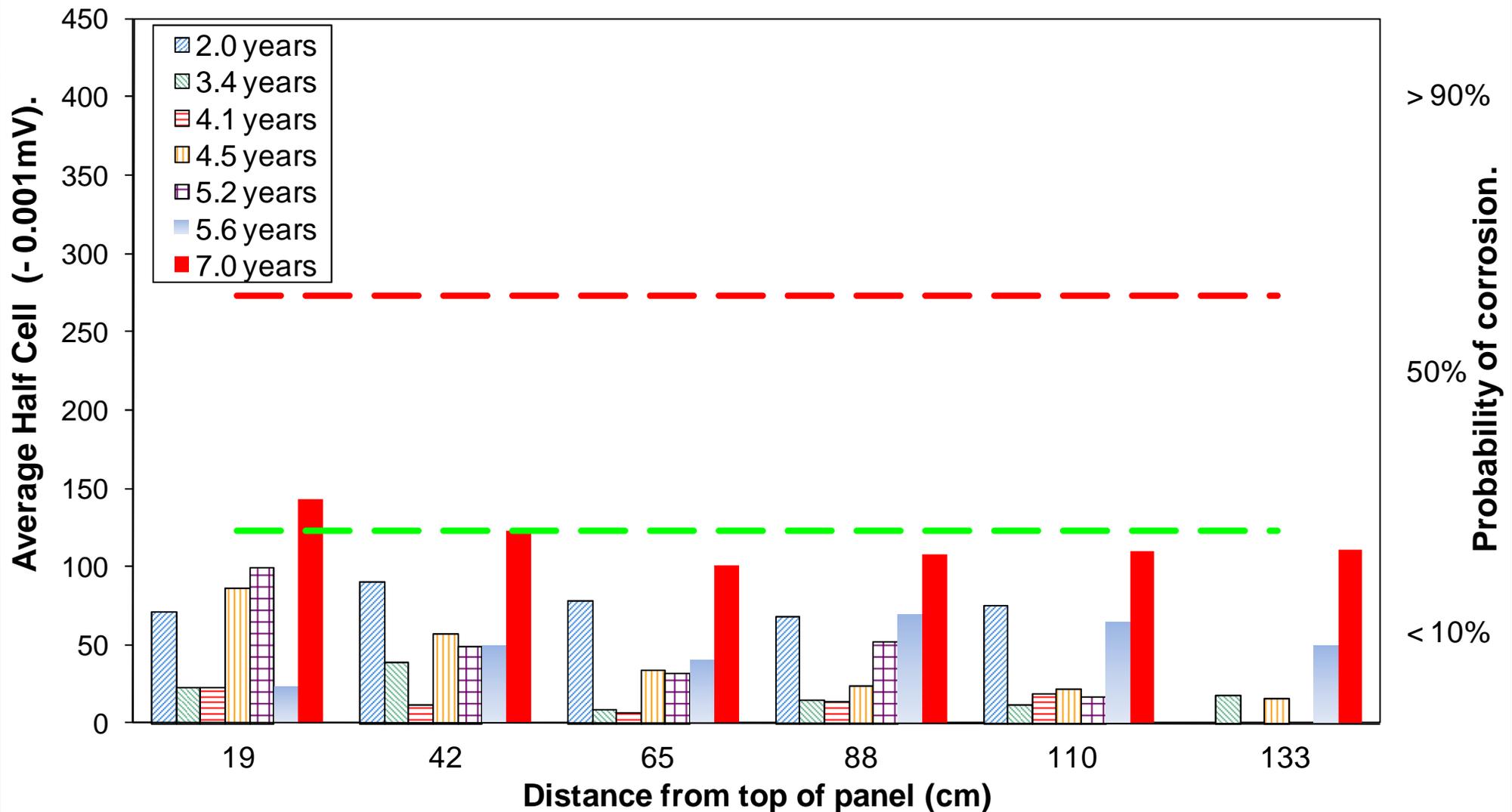
	Default values	Adjusted values
Diffusion coefficient	6.37E-12	3.00E-12
m	0.32	0.35
Corrosion threshold	0.05	0.05

Chloride Concentrations with Life-365 Predictions



Halawa 0.36 w/c; 15% Fly Ash

Panel #12: Halawa 0.36 w/c with 15% Fly Ash



Halawa 0.36 w/c; 15% Fly Ash



CONCLUSIONS

- ❖ The control panel with the lower 0.35 w/c ratio performed better than the 0.40 w/c ratio control panels
- ❖ Corrosion induced cracking was noted after 7 years exposure for the 0.40 w/c ratio control panels

CONCLUSIONS

- ❖ DCI & Rheocrete CNI did not reduce chloride penetration rates (as expected), but delayed onset of corrosion, particularly with a dosage of 20l/m^3
- ❖ Rheocrete 222+ provided inconsistent results

CONCLUSIONS

- ❖ The panels with 5% silica fume gave good results, though poor mixing may have lead to an early failure in one panel
- ❖ The panels with 15% fly ash provided good performance after 7 years of monitoring

CONCLUSIONS

- ❖ Generally, the Life-365 predictions for admixtures analyzed overestimated the chloride levels through each concrete field panel
- ❖ Life-365 default predictions worked well for specimens with silica fume
- ❖ Better default parameters are recommended for fly ash and lower w/c ratio concrete

RECOMMENDATIONS

- ❖ Use lower w/c ratios in concrete mixtures
- ❖ Include replacement of fly ash at 15% or more
- ❖ Include DCI/CNI admixtures at a dosage of $20\ell/m^3$ or more

THANK YOU !

Any questions?



Honolulu, Hawaii