


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Service Life of Bridge Decks
Influence of Cracks

Virginia DOT Workshop – Charlottesville, VA

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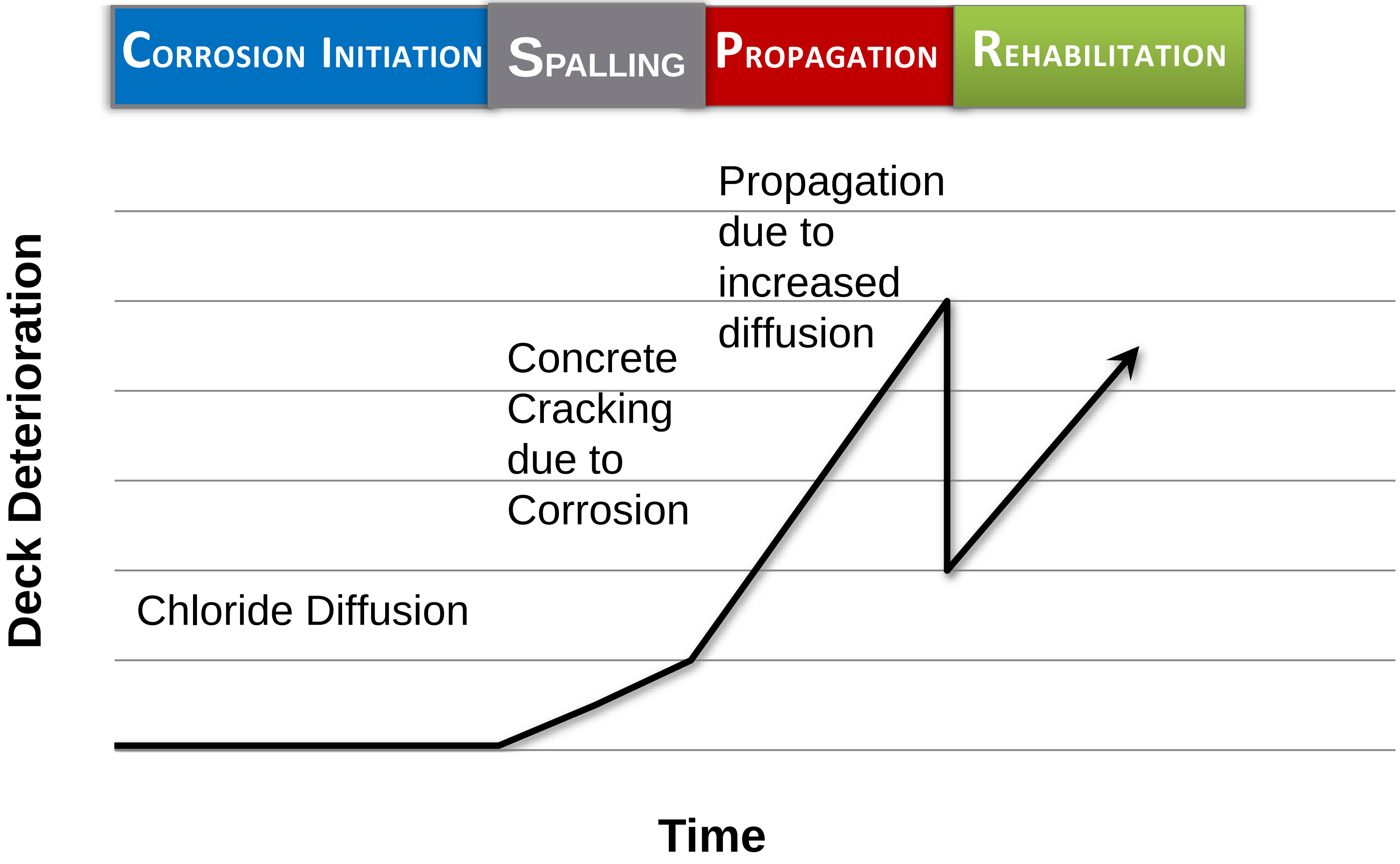
U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

Bridge Deck Damage Curve



Corrosion Service Life

Service Life of Bridge Decks =

Time for corrosion initiation
- ❑ Concrete material properties
- ❑ Concrete cover
- ❑ Reinforcement Type

\+

Time for concrete cracking due to corrosion by-products
- ❑ Reinforcement type
- ❑ Concrete tensile strength

\+

Time for end of functional service life (EOFSL)
- ❑ Vast number of factors affect corrosion propagation
- ❑ Difficult to model

Time for corrosion initiation

How diffusion causes changes in concentration over time

$$C_{x,t} = C_0\left(1 - erf\left(\frac{x}{2\sqrt{D_c t}}\right)\right)$$

Concrete Cover Depth

Chloride at rebar depth

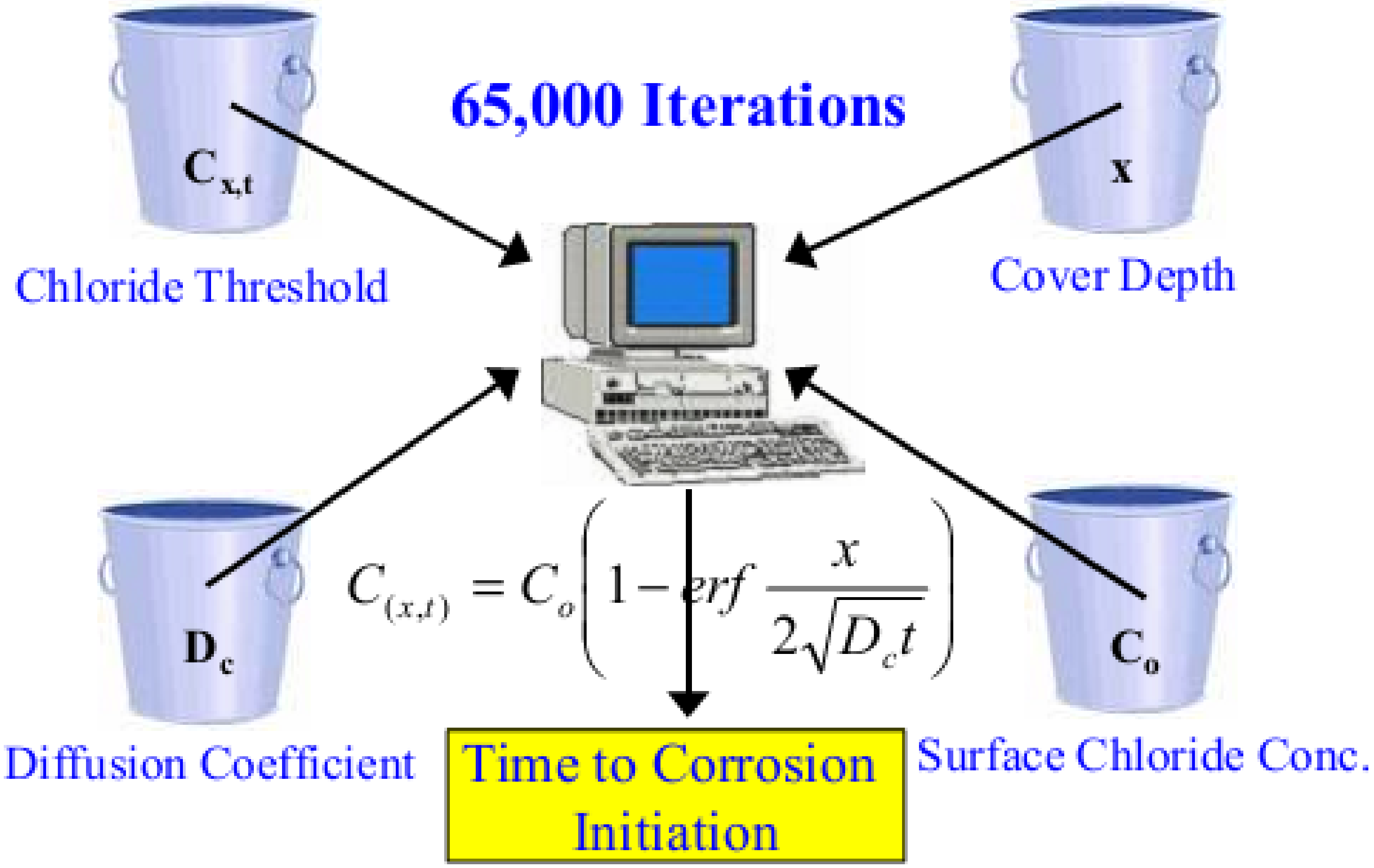
Time (age of concrete)

Surface Chloride

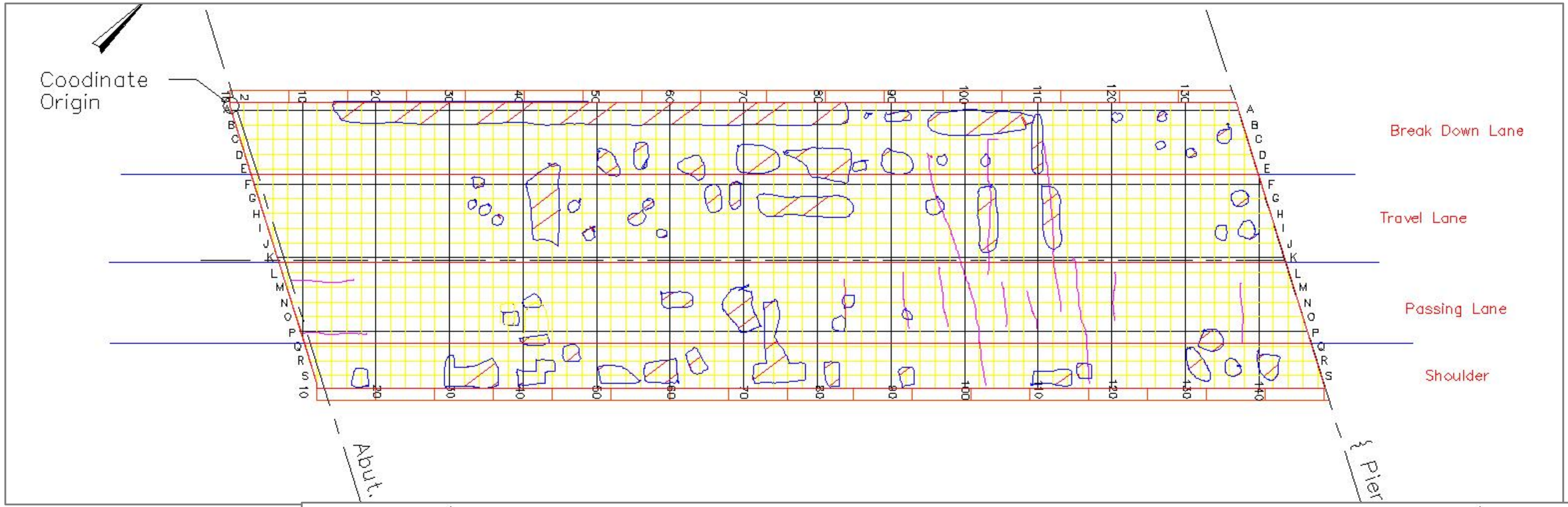
Diffusion Coefficients

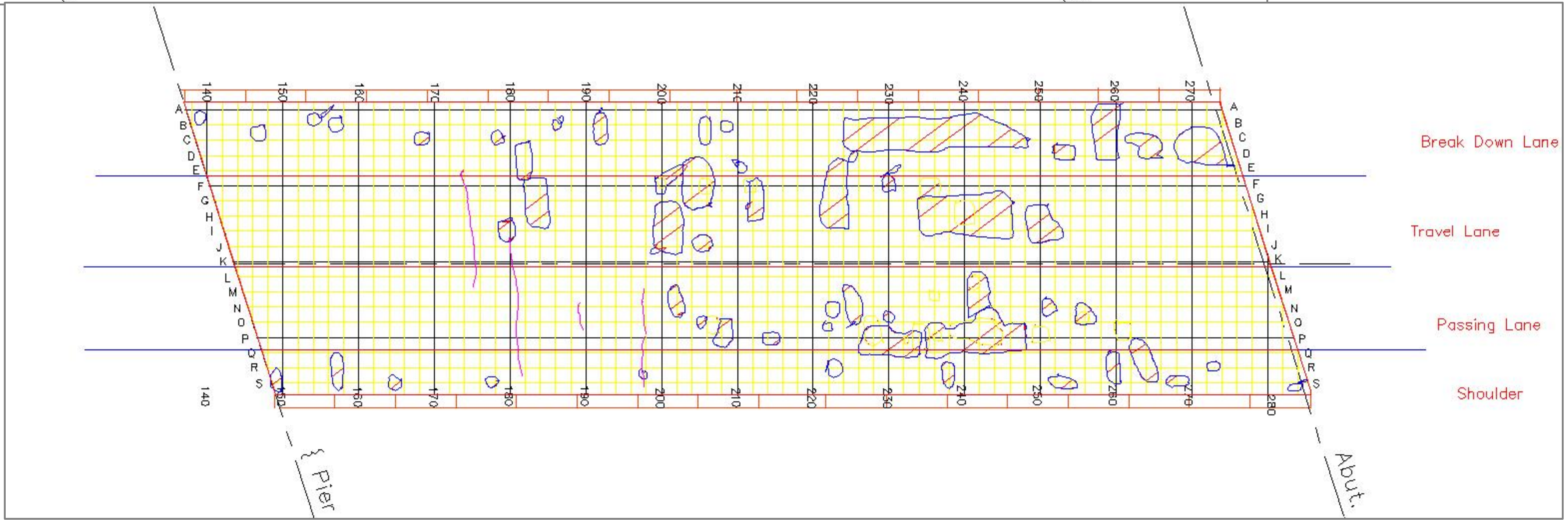
A Solution to
Fick's Second Law

Service Life Routine



Deck Damage Survey

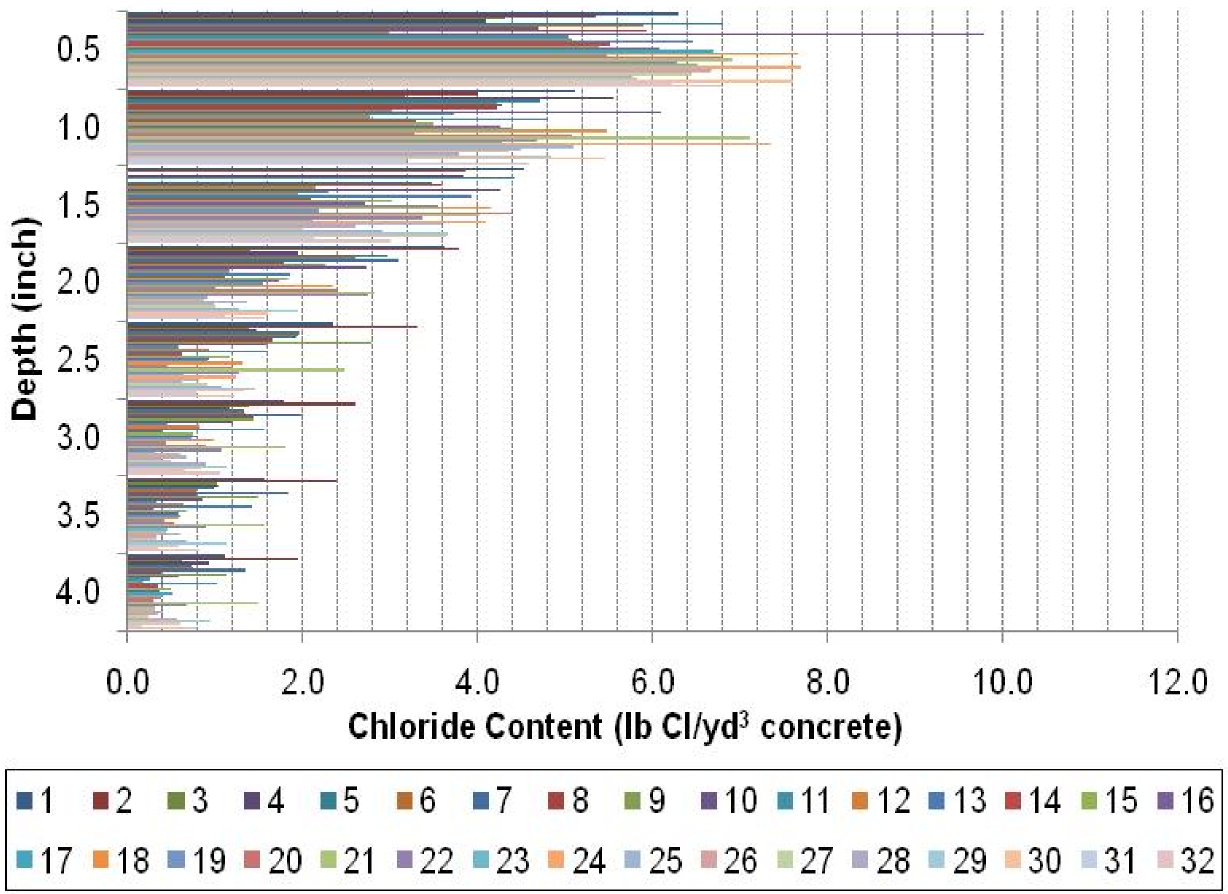




Chloride in Concrete

Many ways to characterize chloride diffusion in concrete:

- Diffusion Coefficient (rate of diffusion)
  - Amount of Chloride in Concrete (ASTM C1152, AASHTO T260)
- Rapid Chloride Permeability (ASTM C1202, AASHTO T277)
- Chloride Migration Coefficients (NordTest Build 492)



Determination of Chloride content

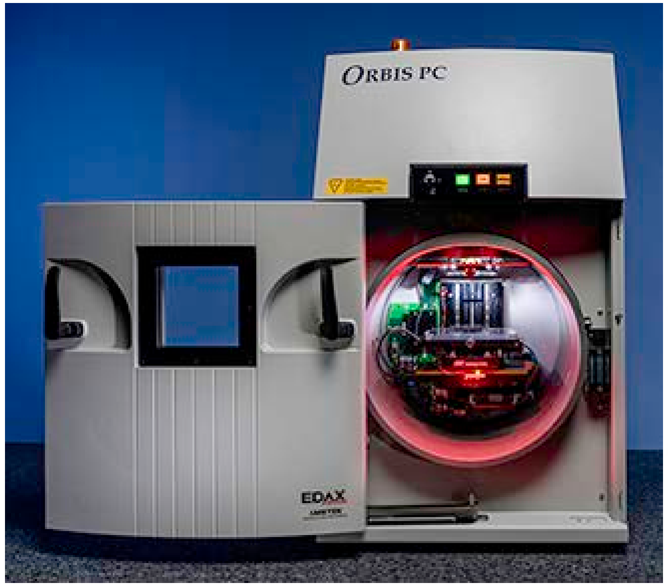
Sampling of concrete for chloride content determination

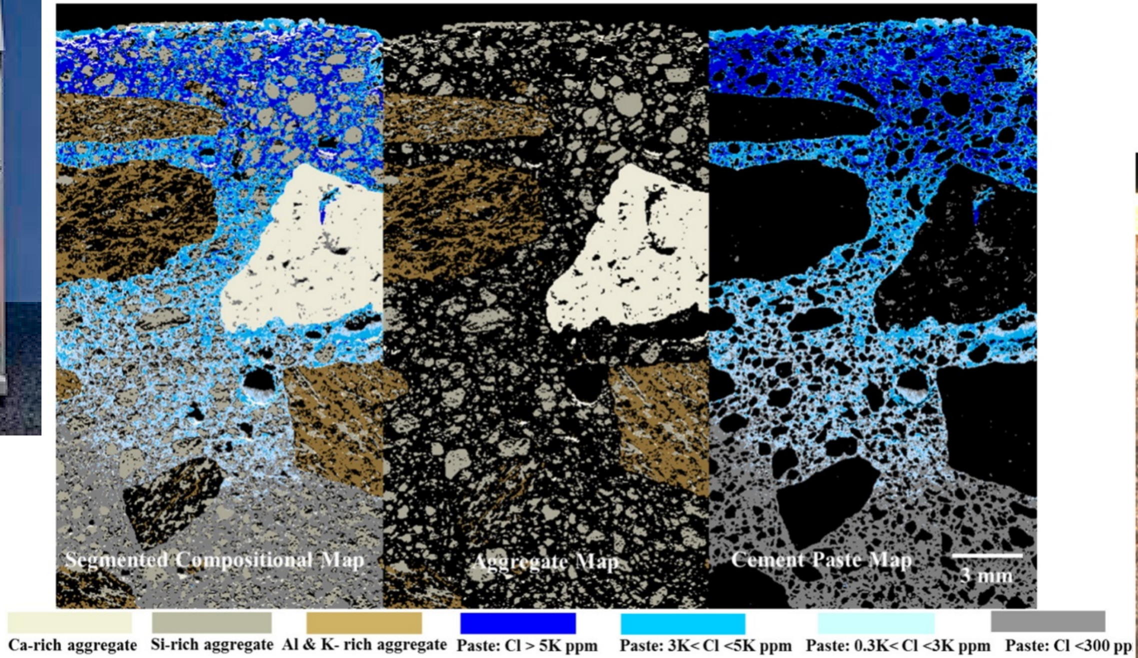
Acid-Soluble Chloride Titration

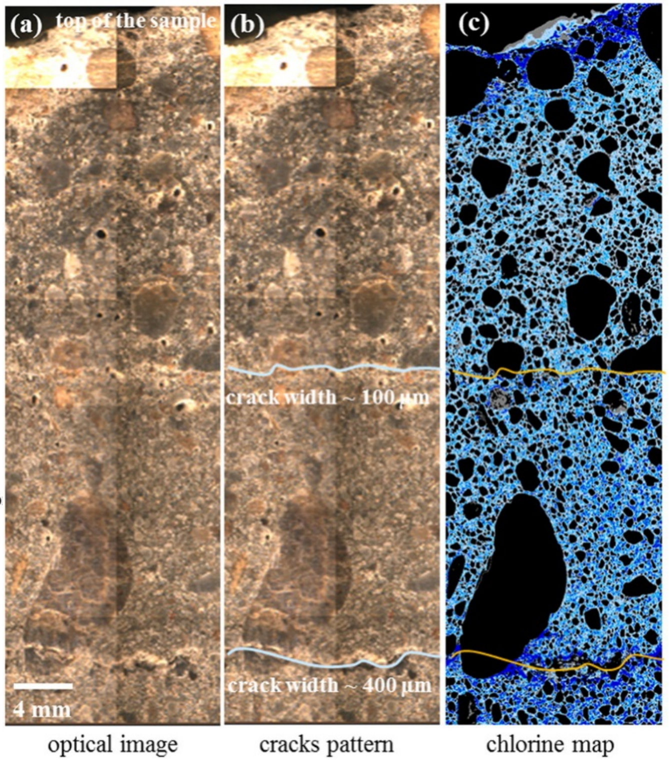
Acid-soluble chloride titration (ASTM C1152, AASHTO T260)

Chloride content in % per mass of concrete

Micro X-ray Fluorescence Technique







Tyler Ley, Associate Professor, Oklahoma State University; EDAX

Concrete Cracking

- Cracking of concrete remains an inevitable problem and can be expensive to repair.

- What is the influence of concrete cracking on the service life of bridge decks?

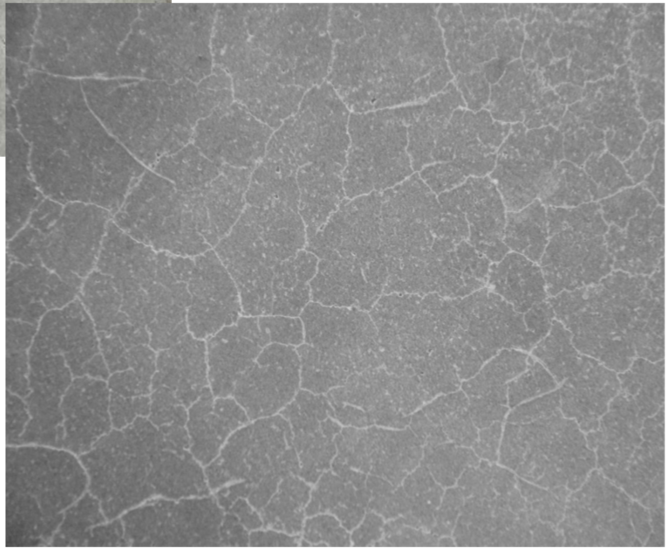
- Cracks form when stresses exceed tensile strength of concrete.

Classification

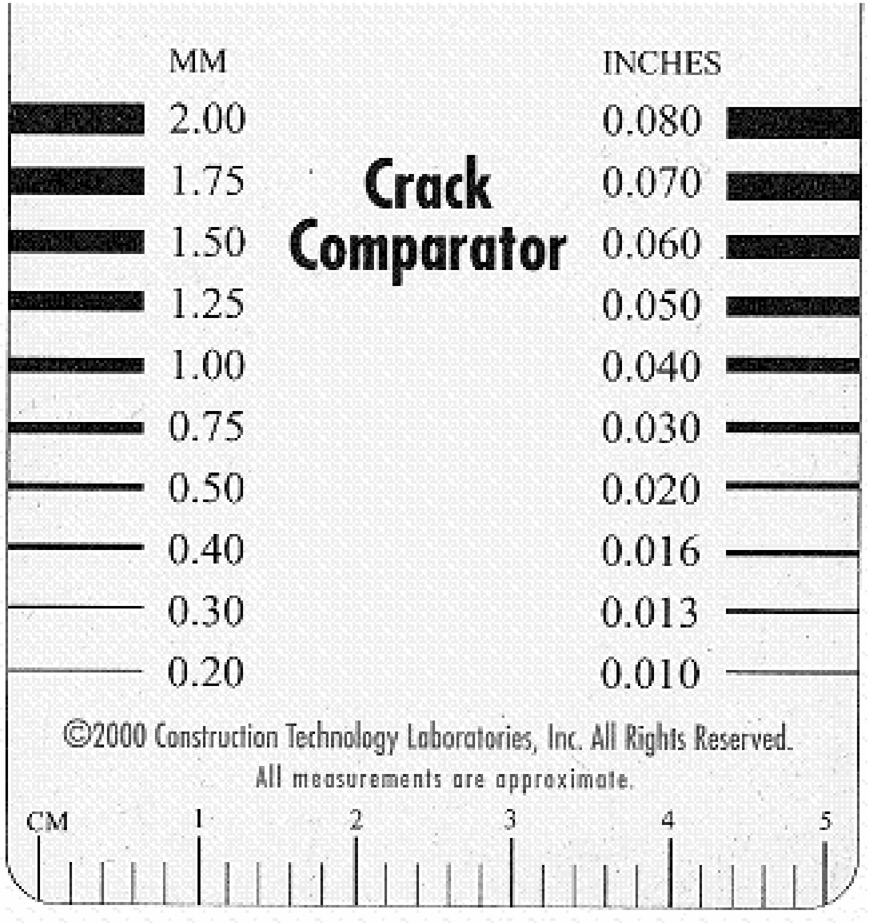
- By Shape
  - Linear cracks
  - Pattern cracks

- By Origin
  - Plastic shrinkage cracks
  - Drying shrinkage cracks
  - Settlement cracks
  - Structural cracks

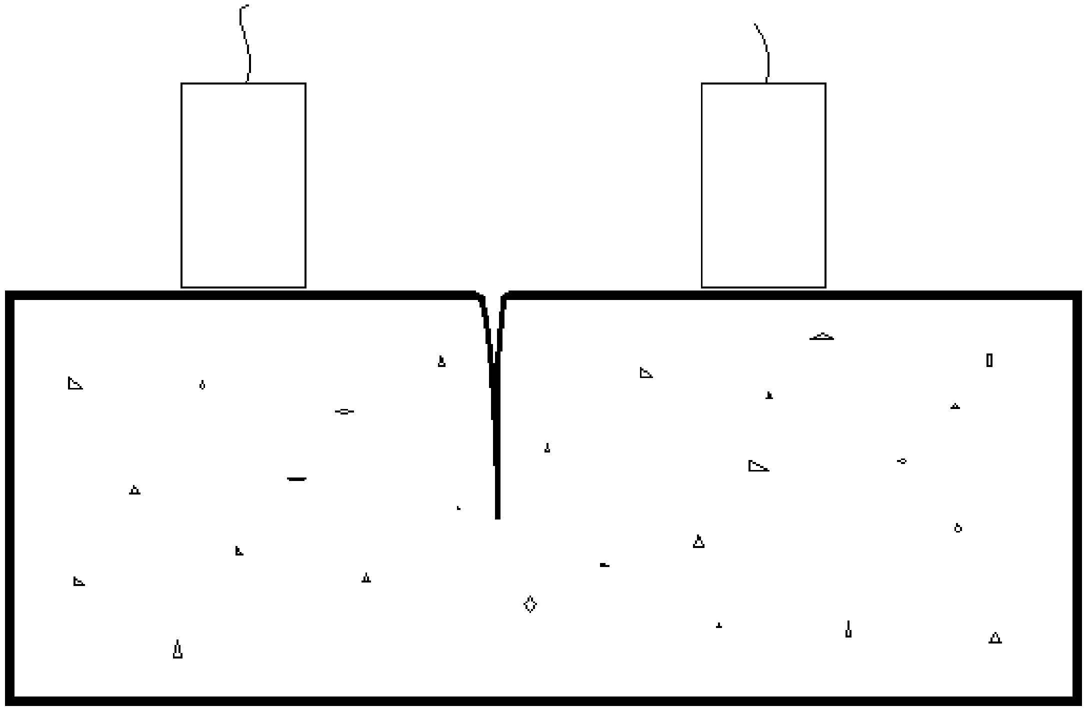
- By Activity
  - Active cracks
  - Passive cracks



Crack Survey Techniques

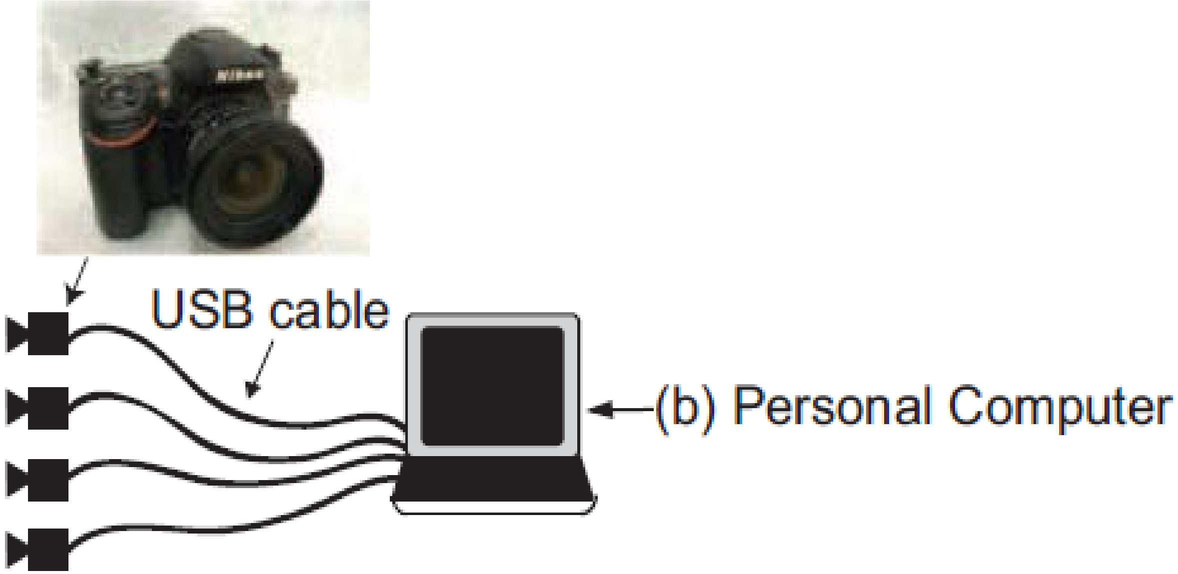


Crack Comparator



Ultrasonic Pulse Velocity – Indirect Configuration

Crack Survey Techniques



Virginia Tech OJOS system

0.008 inch (0.2 mm) maximum resolution at 5 mph

Evaluation of Bridge Decks

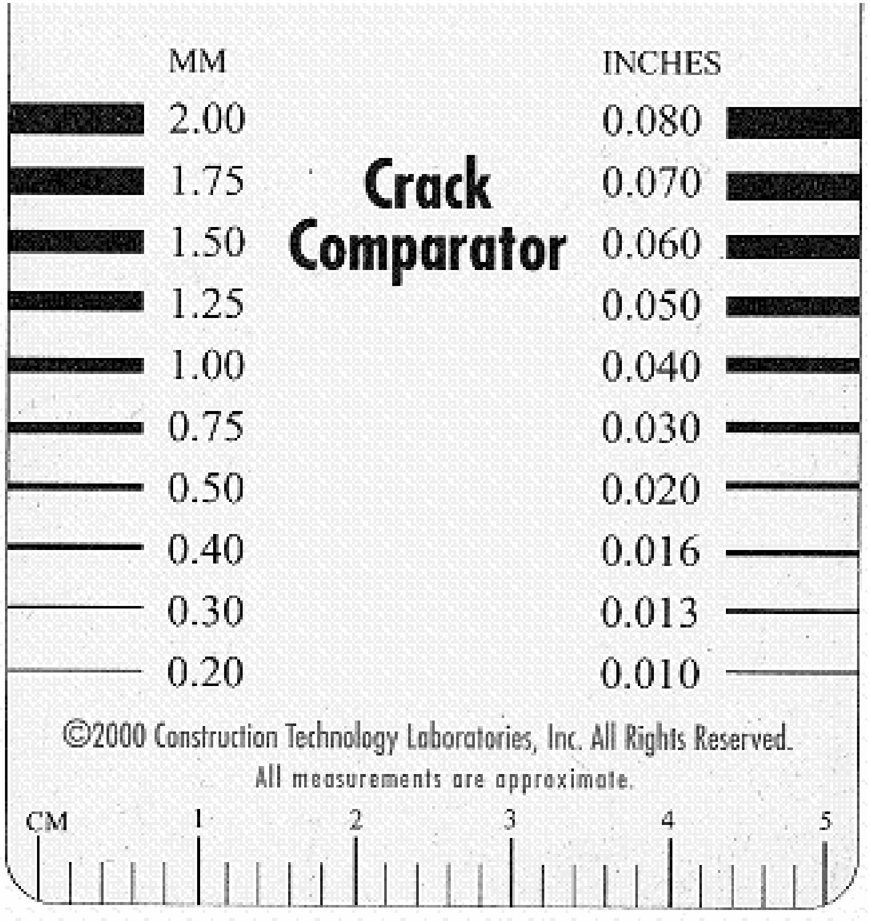
- Thirty seven bare bridge decks were selected.

Groups	**1968-71**	**1984-91**	**1984-91**
Number	10	16	11
Concrete	Plain	Plain	SCM
w/c ratio	0.47	0.45	0.45
Rebar	Black	Epoxy	Epoxy

- Crack survey, damage survey, and core sampling in 2003

Damage Survey

- Damage survey showed almost no damage (<0.5%)
- Length of linear cracks and widths were measured in the field
- Crack depths measured from the cores in the lab

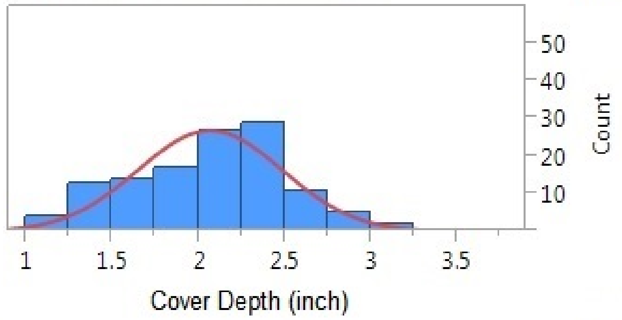


Concrete Material Properties

Groups	68-71 w/c=0.47 No SCM	84-91 w/c=0.45 No SCM	84-91 w/cm=0.45 SCM
Permeability (Coulombs)			
Mean	3766	4793	1361
Std. Dev.	1979	2257	817
Median	3455	5144	1091
C.V.	53%	47%	60%
Pore Space (%)			
Mean	12.7	15.3	13.9
Std. Dev.	1.49	3.9	1.2
Median	12.5	14.7	14
C.V.	12%	25%	9%
Concrete Saturation (%)			
Mean	65	68	76
Std. Dev.	9	6.9	4.1
Median	66	68	75
C.V.	14%	10.1%	5.4%

Cover Depth

a) 68-71 No SCM



Summary Statistics	
Mean	2.06
Std Dev	0.42
N	113
Median	2.12
Mode	2.28

Fitted Normal

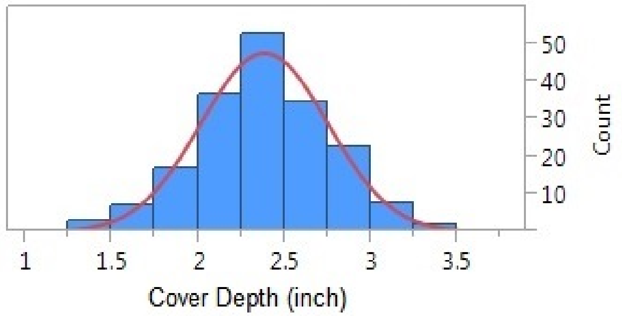
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.976405	0.0429*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

b) 84-91 No SCM



Summary Statistics	
Mean	2.38
Std Dev	0.37
N	176
Median	2.4
Mode	2.4

Fitted Normal

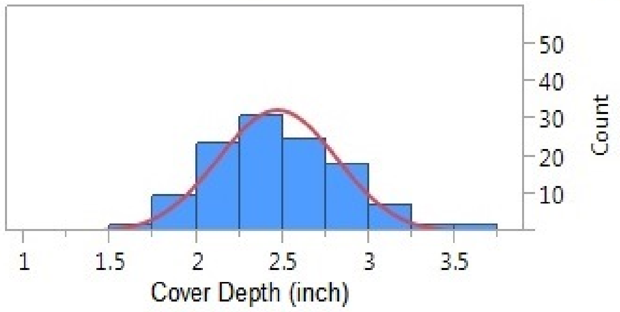
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.992711	0.5247

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

c) 84-91 SCM



Summary Statistics	
Mean	2.46
Std Dev	0.34
N	112
Median	2.4
Mode	2.4

Fitted Normal

Goodness-of-Fit Test

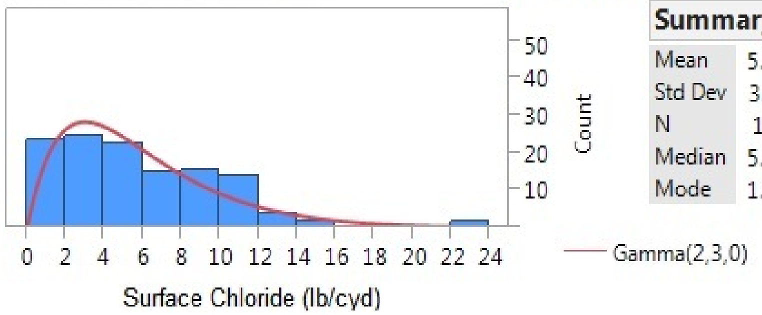
Shapiro-Wilk W Test

W	Prob<W
0.987870	0.4148

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Surface Chloride

a) 68-71 No SCM



Summary Statistics

Mean	5.73
Std Dev	3.93
N	116
Median	5.08
Mode	1.22

Fitted Gamma

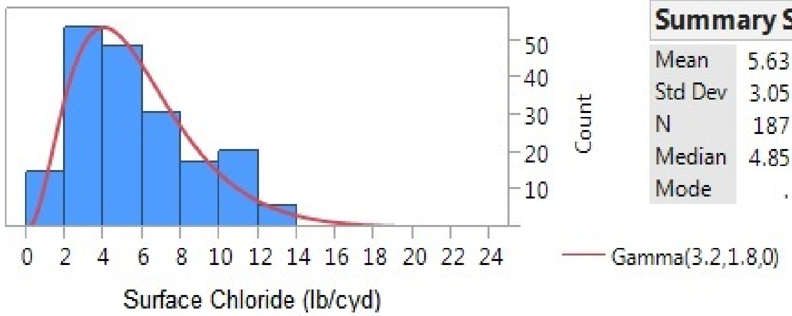
Goodness-of-Fit Test

Cramer-von Mises W Test

W-Square		Prob>W^2
0.144484	>	0.2500

Note: Ho = The data is from the Gamma distribution. Small p-values reject Ho.

b) 84-91 No SCM



Summary Statistics

Mean	5.63
Std Dev	3.05
N	187
Median	4.85
Mode	.

Fitted Gamma

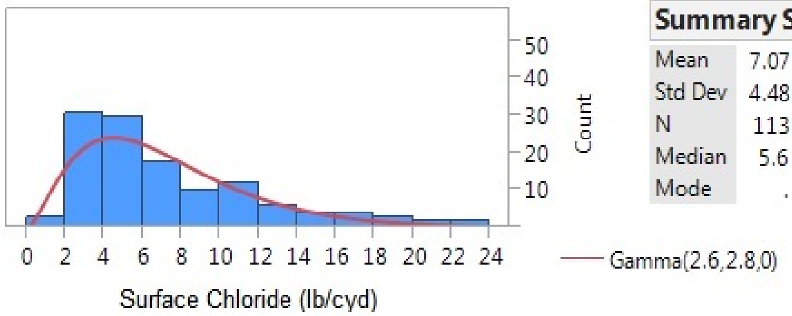
Goodness-of-Fit Test

Cramer-von Mises W Test

W-Square		Prob>W^2
0.116920	>	0.2500

Note: Ho = The data is from the Gamma distribution. Small p-values reject Ho.

c) 84-91 SCM



Summary Statistics

Mean	7.07
Std Dev	4.48
N	113
Median	5.6
Mode	.

Fitted Gamma

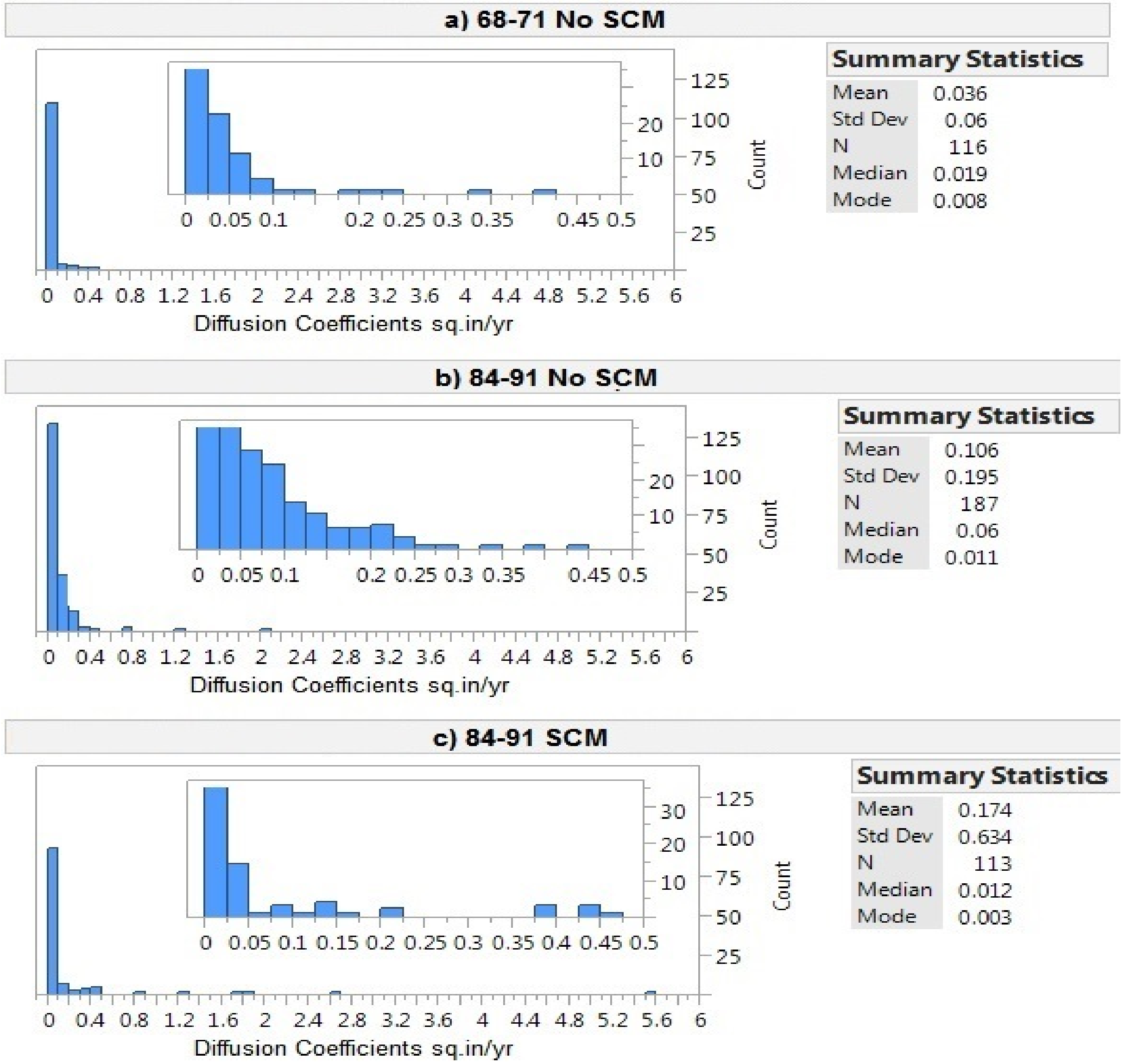
Goodness-of-Fit Test

Cramer-von Mises W Test

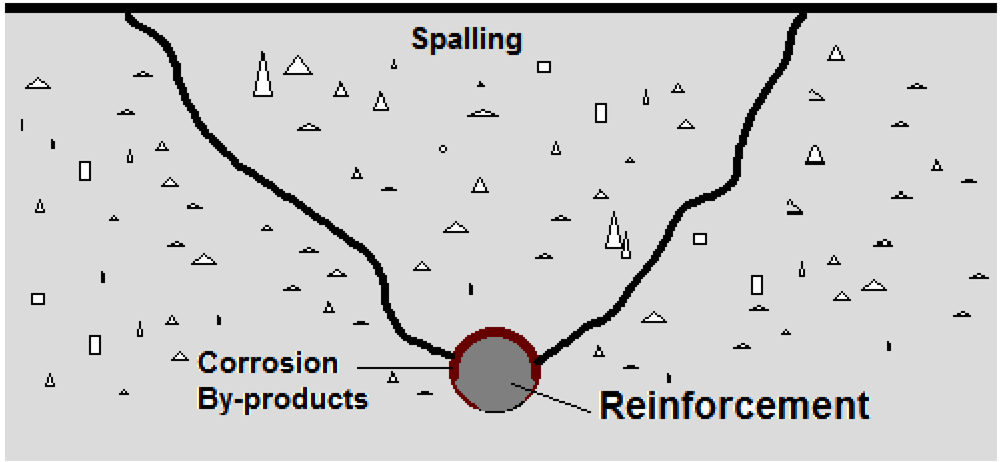
W-Square		Prob>W^2
0.203726	>	0.2500

Note: Ho = The data is from the Gamma distribution. Small p-values reject Ho.

Diffusion Coefficients



Crack Influence

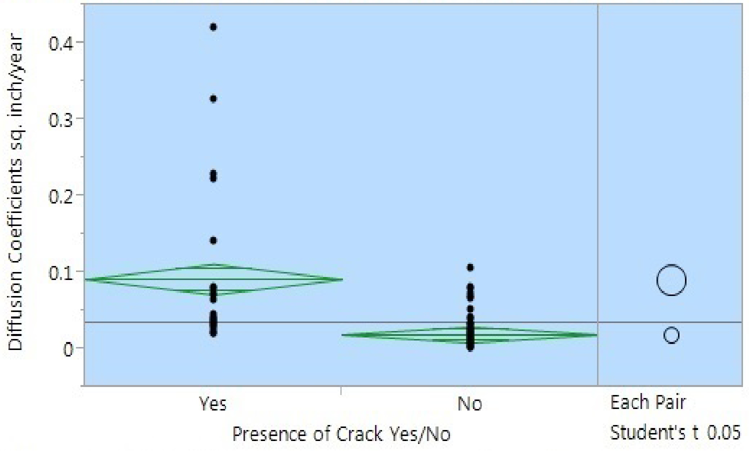


$$\frac{\left\{\left[\tan 45^{\circ} \times \left(\frac{2}{12}'\right)\right] \times 2 \times 1'\right\}}{(1' \times 1')} = 0.33\ \frac{ft^2}{ft^2}$$

Thus, 1 ft/ft^2 crack frequency influences 33.3% of one square foot of deck area.

Chloride Diffusion at Cracked Locations

a) Oneway Analysis of Diffusion Coefficients sq. inch/year By Presence of Crack Yes/No



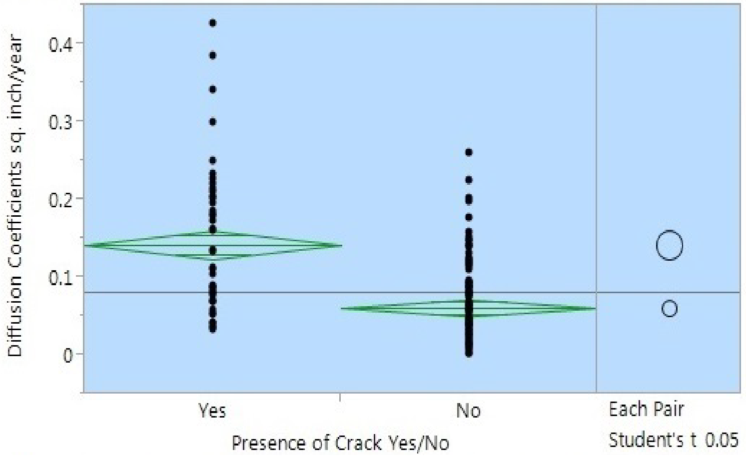
Comparisons for each pair using Student's t

Connecting Letters Report

Level		Mean
Yes	A	0.091
No	B	0.019

Levels not connected by same letter are significantly different.

b) Oneway Analysis of Diffusion Coefficients sq. inch/year By Presence of Crack Yes/No



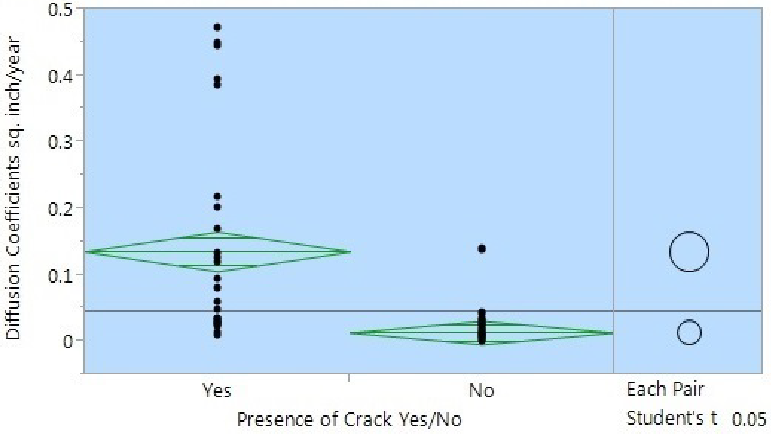
Comparisons for each pair using Student's t

Connecting Letters Report

Level		Mean
Yes	A	0.142
No	B	0.061

Levels not connected by same letter are significantly different.

c) Oneway Analysis of Diffusion Coefficients sq. inch/year By Presence of Crack Yes/No



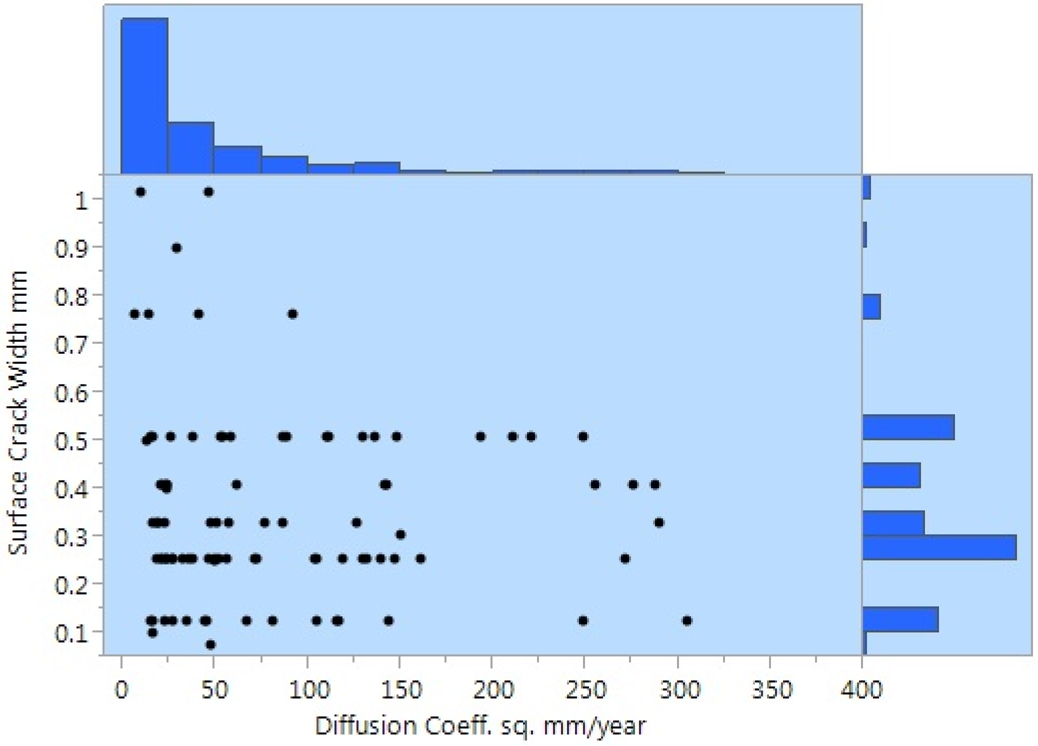
Comparisons for each pair using Student's t

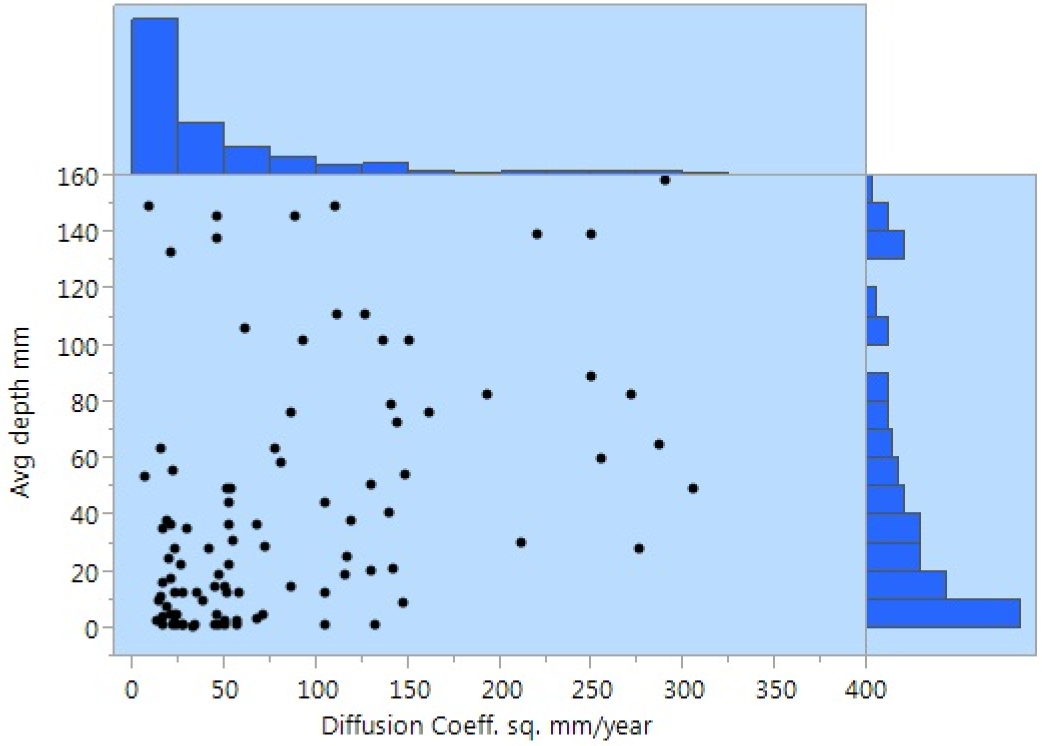
Connecting Letters Report

Level		Mean
Yes	A	0.135
No	B	0.014

Levels not connected by same letter are significantly different.

Crack Widths & Depths vs. Chloride Diffusion

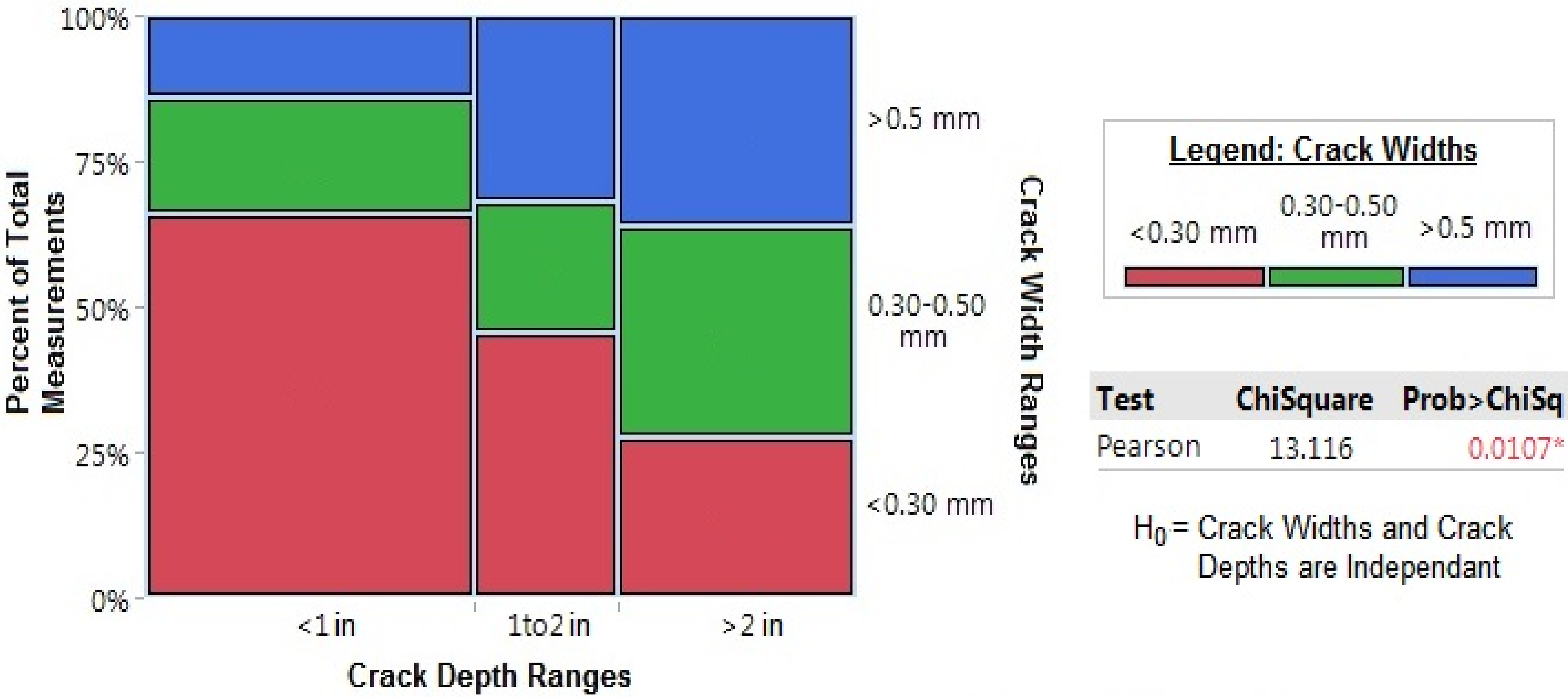




Crack Width Threshold

AASHTO 7th Edition	0.017 inch	0.43 mm
Mangat (1987)	0.008 inch	0.2 mm
NCHRP 380 (1996)	As narrow as 0.002 inch	0.05 mm
Xi et al (2003)	0.004 to 0.008 inch	0.1 to 0.2 mm
Ismail et al (2008)	0.002 inch	0.06 mm

Crack Width vs Depth



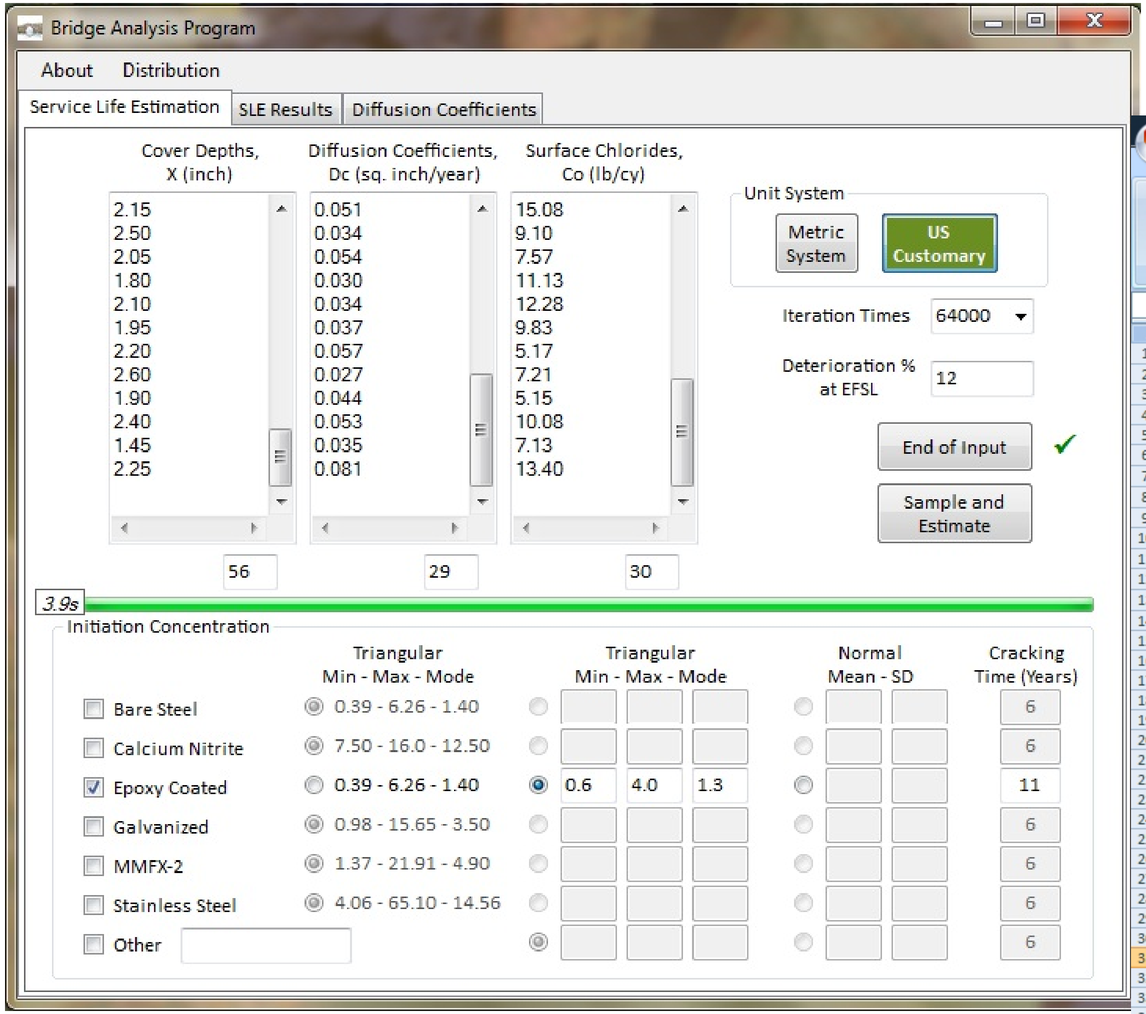
Test	ChiSquare	Prob>ChiSq
Pearson	13.116	0.0107*

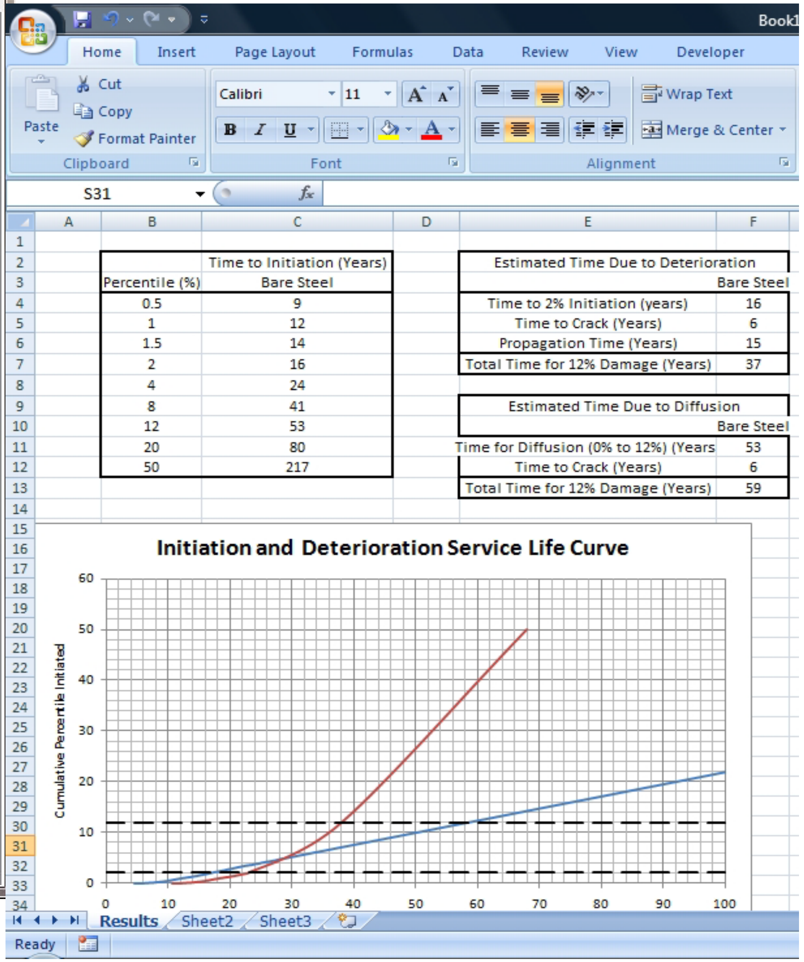
H_0 = Crack Widths and Crack Depths are Independant

Classification of Diffusion

Cracked/ Uncracked	Crack Frequency	Diffusion at Cracks	Crack Influenced Deck Area and Number of Data					
			0.47 w/cm No-SCM (years)		0.45 w/cm No-SCM (years)		0.45 w/cm SCM (years)	
			Freq, #	D_c in²/yr	Freq, #	D_c in²/yr	Freq, #	D_c in²/yr
Cracked	Low Frequency	Low Diffusion	2%, 2	0.020 – 0.022	3%, 4	0.033 – 0.037	3%, 3	0.009 – 0.023
		Median Diffusion		0.042 – 0.045		0.110 – 0.136		0.081 – 0.095
		High Diffusion		0.327 – 0.420		0.386 – 1.297		1.748 – 2.651
Cracked	Median Frequency	Low Diffusion	5%, 5	0.020 – 0.029	9%, 14	0.033 – 0.078	7%, 6	0.009 – 0.025
		Median Diffusion		0.042 – 0.071		0.084 – 0.172		0.050 – 0.119
		High Diffusion		0.143 – 0.420		0.202 – 1.297		0.450 – 2.651
Cracked	High Frequency	Low Diffusion	16%, 17	0.020 – 0.073	25%, 46	0.033 – 0.386	15%, 14	0.009 – 0.059)
		Median Diffusion		0.029 – 0.143		0.036 – 0.428		0.031 – 0.202
		High Diffusion		0.037 – 0.420		0.037 – 1.297		0.126 – 2.651
Uncracked	--	--	91	0.0015 – 0.186	137	0.0015 – 0.741	80	0.0015 – 0.897

Service Life Model Program





Service Life of Uncracked Concrete

Groups	0.47 w/cm No SCM	0.45 w/cm No SCM	0.45 w/cm SCM
	Uncracked (years)	Uncracked (years)	Uncracked (years)
Time for corrosion initiation (0% to 2% Deck Damage)	16	8	28
Time for Diffusion (0% to 12% Deck Damage)	47	20	105

Time to Corrosion Initiation – Uncoated Bars

Degree of Crack Frequencies	Category	68-71, 0.47 w/c, no SCM	84-91, 0.45 w/c, no SCM	84-91, 0.45 w/c, SCM
Uncracked	Uncracked	15	8	28
Low Frequency	Low Diffusion	15	8	28
	Median Diffusion	14	8	19
	High Diffusion	10	6	4
Median Frequency	Low Diffusion	15	8	28
	Median Diffusion	13	7	16
	High Diffusion	7	5	3
High Frequency	Low Diffusion	13	6	23
	Median Diffusion	11	6	11
	High Diffusion	6	5	3

VDOT Corrosion Resistant Reinforcement

- **Corrosion Resistant Reinforcing Steel, Class I** shall conform to ASTM A1035/A1035M – Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement

- **Corrosion Resistant Reinforcing Steel, Class II** shall conform to AASHTO Designation: MP 13M/MP 13-04, Standard Specification for Stainless Steel Clad Deformed and Plain Round Steel Bars for Concrete Reinforcement

- **Corrosion Resistant Reinforcing Steel, Class III** shall conform to ASTM A955/A955M – Standard Specification for Deformed and Plain Solid Stainless Steel Bars for Concrete Reinforcement.

Time to Corrosion Initiation – Corrosion Resistant Rebar

Degree of Crack Frequencies	Category	A1035 Rebar (years)	A955 Steel (years)
Uncracked	Uncracked	150+	150+
Low Frequency	Low Diffusion	150+	150+
	Median Diffusion	150+	150+
	High Diffusion	100+	150+
Median Frequency	Low Diffusion	150+	150+
	Median Diffusion	100+	150+
	High Diffusion	56	150+
High Frequency	Low Diffusion	100+	150+
	Median Diffusion	64	150+
	High Diffusion	30	150+

Service Life of Corrosion Resistant Reinforcement

Degree of Crack Frequencies	Category	A1035 Rebar (years)	A955 Steel (years)
Uncracked	Uncracked	150+	150+
Low Frequency	Low Diffusion	150+	150+
	Median Diffusion	150+	150+
	High Diffusion	150+	150+
Median Frequency	Low Diffusion	150+	150+
	Median Diffusion	150+	150+
	High Diffusion	150+	150+
High Frequency	Low Diffusion	150+	150+
	Median Diffusion	150+	150+
	High Diffusion	150+	150+

Conclusions

- Concrete cracking allows significantly higher chloride diffusion compared to uncracked concrete locations.

- Surface crack widths do not have a strong correlation with the rate of chloride diffusion; however crack depths exhibited a strong correlation.

- Time to corrosion initiation in bridge decks built with relatively less permeable concrete with supplementary cementitious materials was affected significantly, while the older mix design with plain OPC was not sensitive to the presence of cracks.

Conclusions

- Time to end-of-functional-service-life is difficult to model and needs more information to improve reliability.

- VDOT's recently used concrete mix with corrosion resistant reinforcement, A1035 (MMFX-2) and A955 (Stainless Steel), was considerably durable compared to the bare steel.

Thank you