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INFLUENCE OF CRACKS ON CORROSION INITIATION OF CORROSION RESISTANT REINFORCEMENT

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EVALUATION OF BRIDGE DECKS

- Twenty seven bare bridge decks were selected from all exposure zones.
    - w/c or w/cm ratio = 0.45, built between 1984 and 1991 with epoxy coated rebar
        - » 16 decks with PC concrete
        - » 7 decks with GGBFS
        - » 4 decks with fly ash

Zone	Environmental Zone Description	Notation	Salt Usage (kg-Cl-/lane-km)
1	Southwest Mountain	SM	688
2	Central Mountain	CM	671
3	Western Piedmont	WP	220
4	Northern	N	4369
5	Eastern Piedmont	EP	530
6	Tidewater	TW	225

- Crack survey, damage survey, and core sampling

- At time of survey (2003), the decks were in service 12 to 19 years

SURVEY RESULTS

- Damage survey showed almost no damage (< 0.5% spalls, delaminations and patches)

- Crack widths and crack depths were measured to determine if deck cracking influences chloride diffusion rate and the associated influence on corrosion resistant service life

- Coring included companion cores with and without cracks

CRACK SURVEY RESULTS

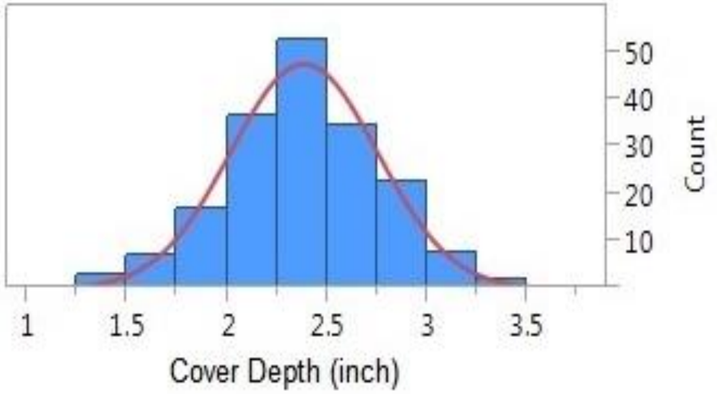
Subgroups	1984-91 No-SCM	1984-91 SCM
N	16	11
Longitudinal Crack Frequency (ft/ft^2)		
Mean	0.163	0.100
Std. Dev.	0.121	0.085
Transverse Crack Frequency (ft/ft^2)		
Mean	0.073	0.079
Std. Dev.	0.090	0.055
Diagonal Crack Frequency (ft/ft^2)		
Mean	0.007	0.013
Std. Dev.	0.011	0.038
Total Crack Frequency (ft/ft^2)		
Mean	0.246	0.192
Std. Dev.	0.187	0.093

CONCRETE MATERIAL PROPERTIES

Groups	w/c=0.45 No SCM	w/cm=0.45 SCM
Permeability (Coulombs)		
Mean	4793	1361
Std. Dev.	2257	817
Median	5144	1091
C.V.	47%	60%
Pore Space (%)		
Mean	15.3	13.9
Std. Dev.	3.9	1.2
Median	14.7	14
C.V.	25%	9%
Concrete Saturation (%)		
Mean	68	76
Std. Dev.	6.9	4.1
Median	68	75
C.V.	10.1%	5.4%

COVER DEPTH

b) 84-91 No SCM



Summary Statistics

Mean	2.38
Std Dev	0.37
N	176
Median	2.4
Mode	2.4

Fitted Normal

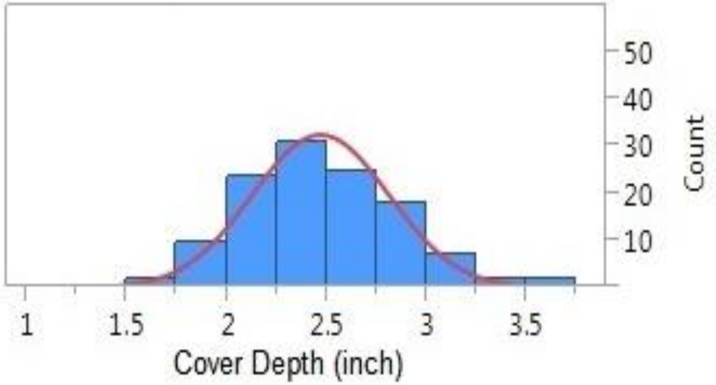
Goodness-of-Fit Test

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

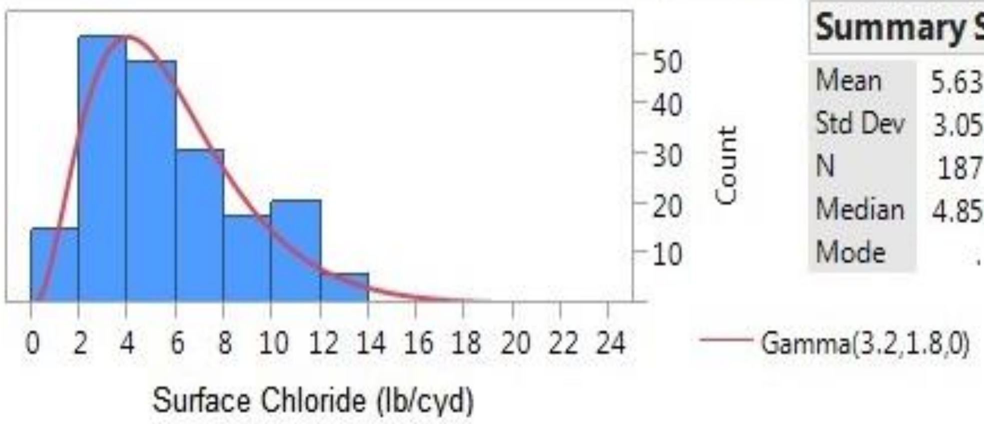
Shapiro-Wilk W Test

W	Prob<W
0.987870	0.4148

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

SURFACE CHLORIDE

b) 84-91 No SCM



Summary Statistics

Mean	5.63
Std Dev	3.05
N	187
Median	4.85
Mode	.

Fitted Gamma

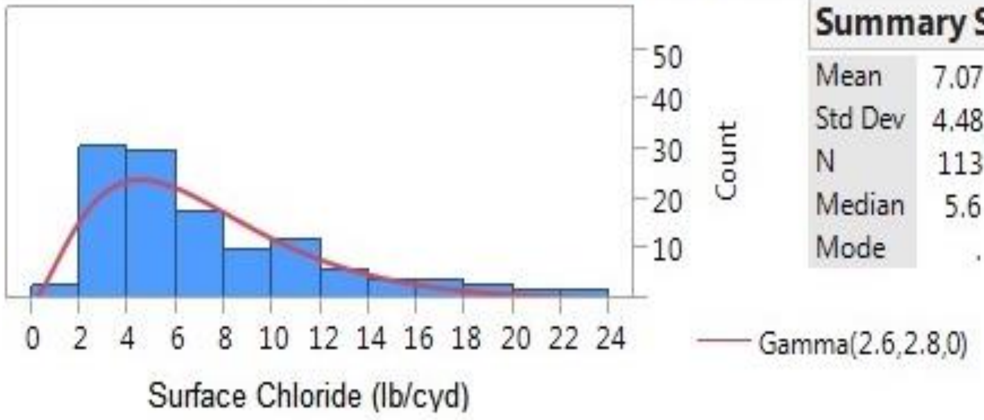
Goodness-of-Fit Test

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

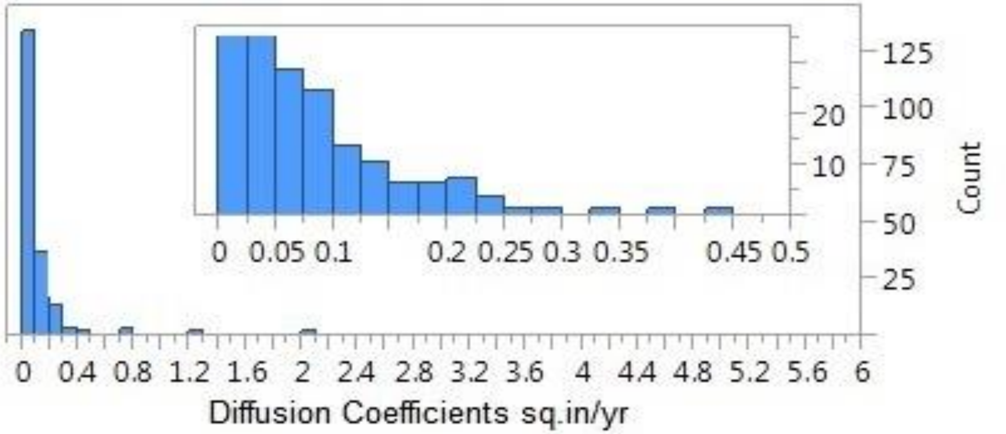
Cramer-von Mises W Test

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

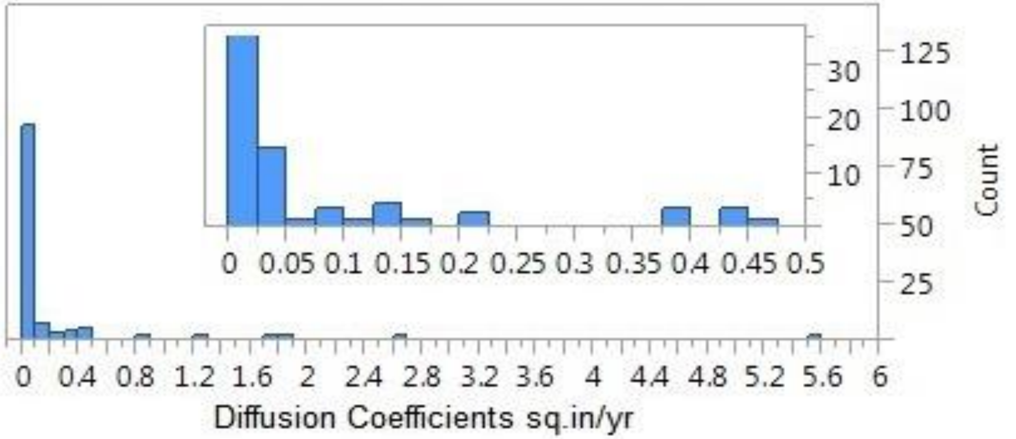
b) 84-91 No SCM



Summary Statistics

Mean	0.106
Std Dev	0.195
N	187
Median	0.06
Mode	0.011

c) 84-91 SCM



Summary Statistics

Mean	0.174
Std Dev	0.634
N	113
Median	0.012
Mode	0.003

CRACK INFLUENCE ON CHLORIDE DIFFUSION

NO SCM

Parameter	Hypothesized Value	Actual Estimate = Cracked - Uncracked	Prob. > |t| Two tail	Prob. > t Right tail	Prob. < t Left tail
Cl- at rebar depth (lb/yd³)	0	1.15	**<.0001**	**<.0001**	1.000
Diffusion coefficient (in²/yr.)	0	0.17	**<.0001**	**<.0001**	1.000
Surface rust area (%)	0	0.08	0.893	0.446	0.554
Moisture saturation (%)	0	2.75	**0.009**	**0.005**	0.995

CRACK INFLUENCE ON CHLORIDE DIFFUSION

SCM

Parameter	Hypothesized Value	Actual Estimate = Cracked - Uncracked	Prob. > |t| Two Tail	Prob. > t Right Tail	Prob. < t Left Tail
Cl- at rebar depth (lb/yd^3)	0	2.11	**0.000**	**0.000**	1.000
Diffusion coefficient ($in^2/yr.$)	0	0.533	**0.000**	**0.000**	1.000
Surface rust area (%)	0	2.62	0.279	0.139	0.861
Moisture saturation (%)	0	8.88	**0.000**	**0.000**	1.000

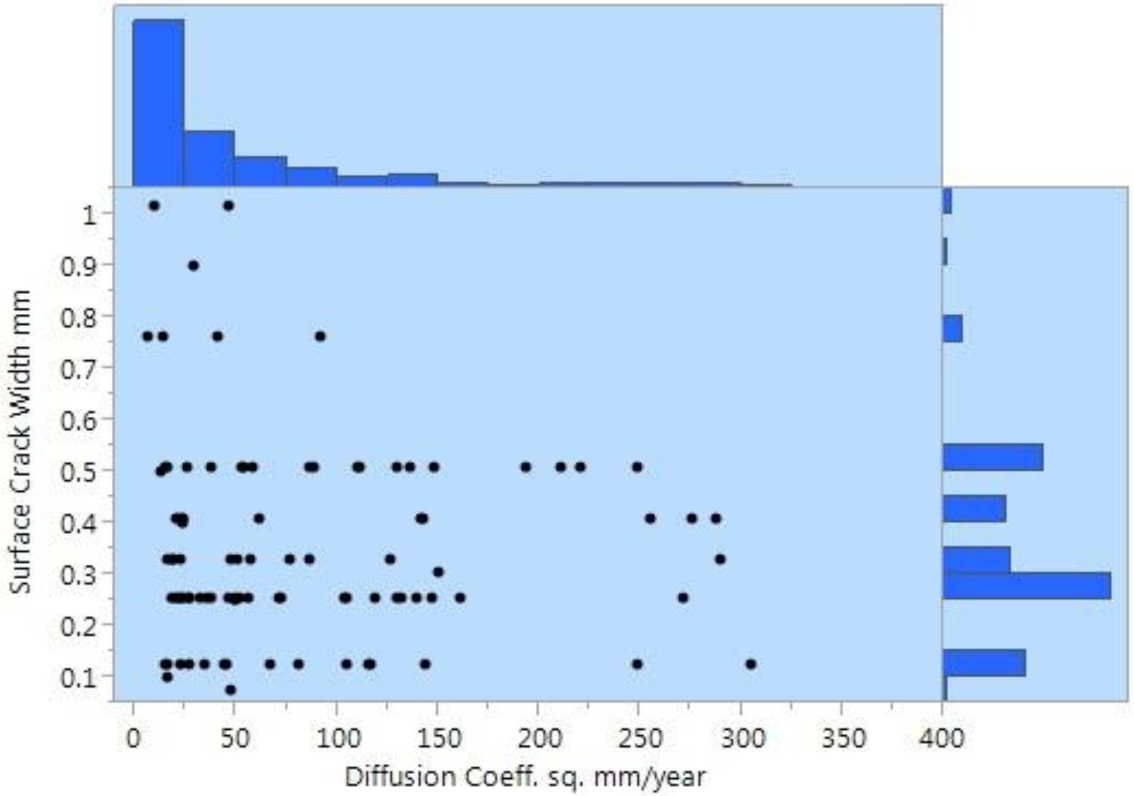
CONCLUSION (1 OF 4)

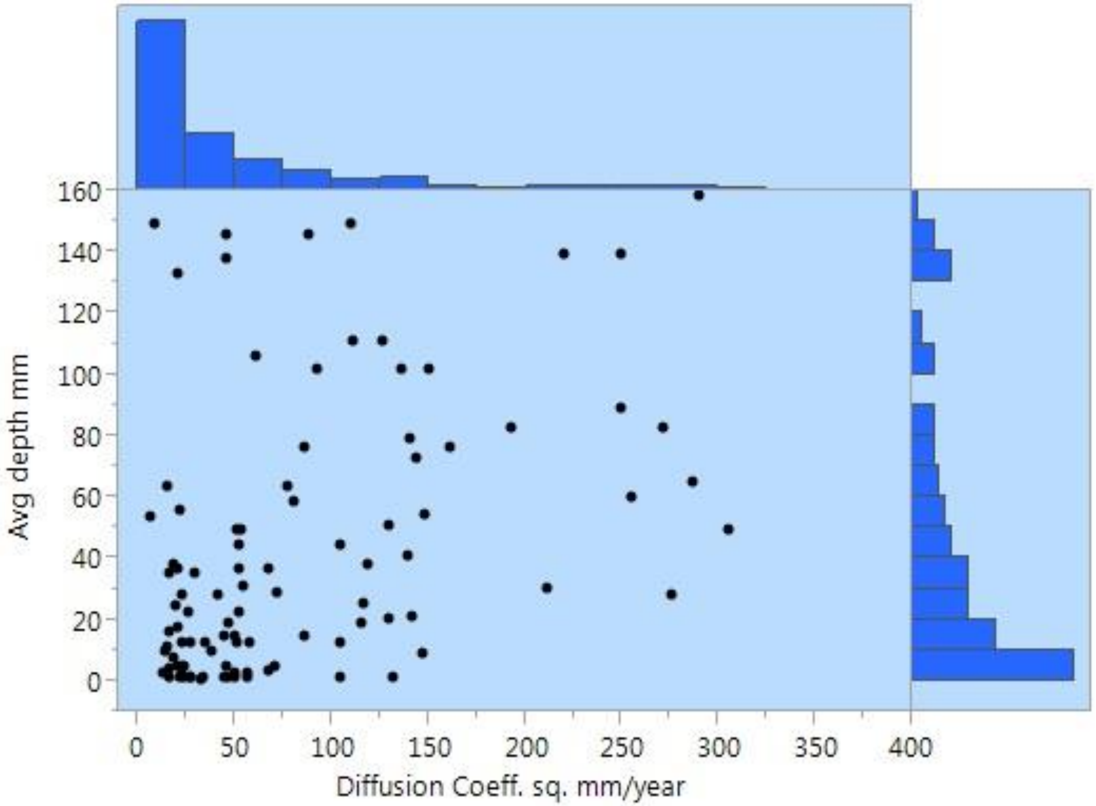
- Concrete cracking allows significantly higher chloride diffusion compared to uncracked concrete locations.

CRACK WIDTH

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

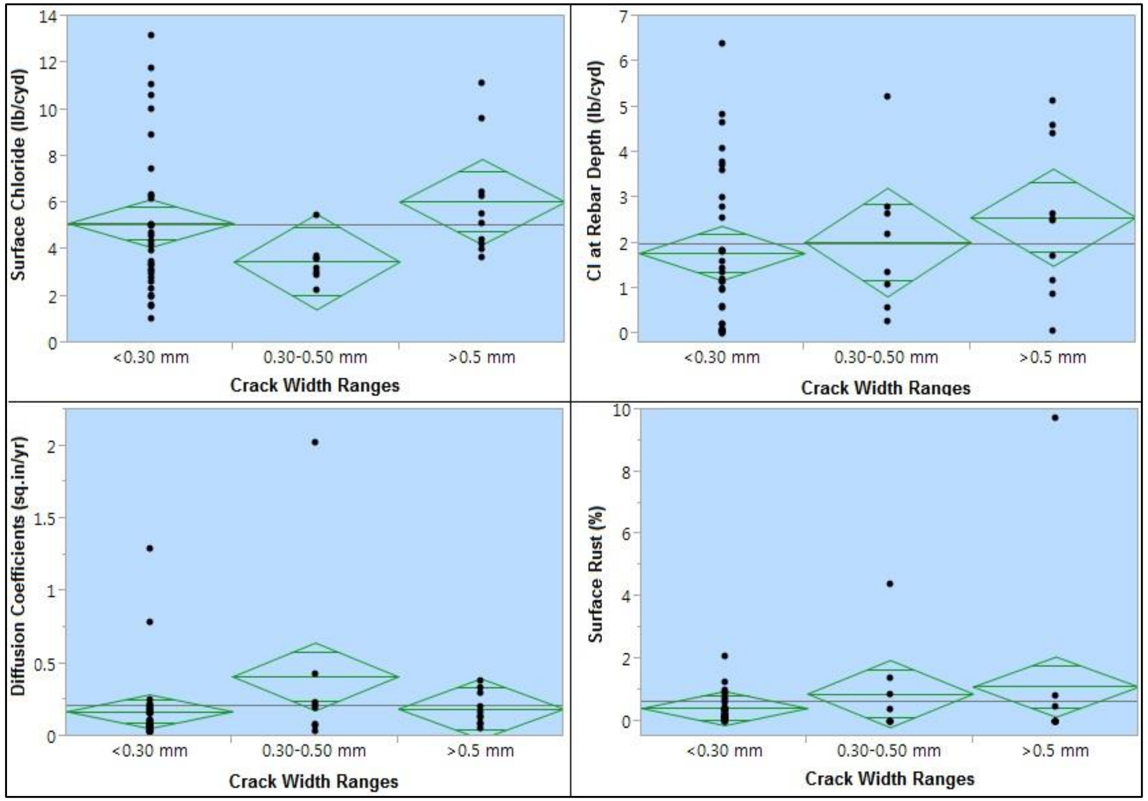
CRACK DIMENSIONS VS. CHLORIDE DIFFUSION

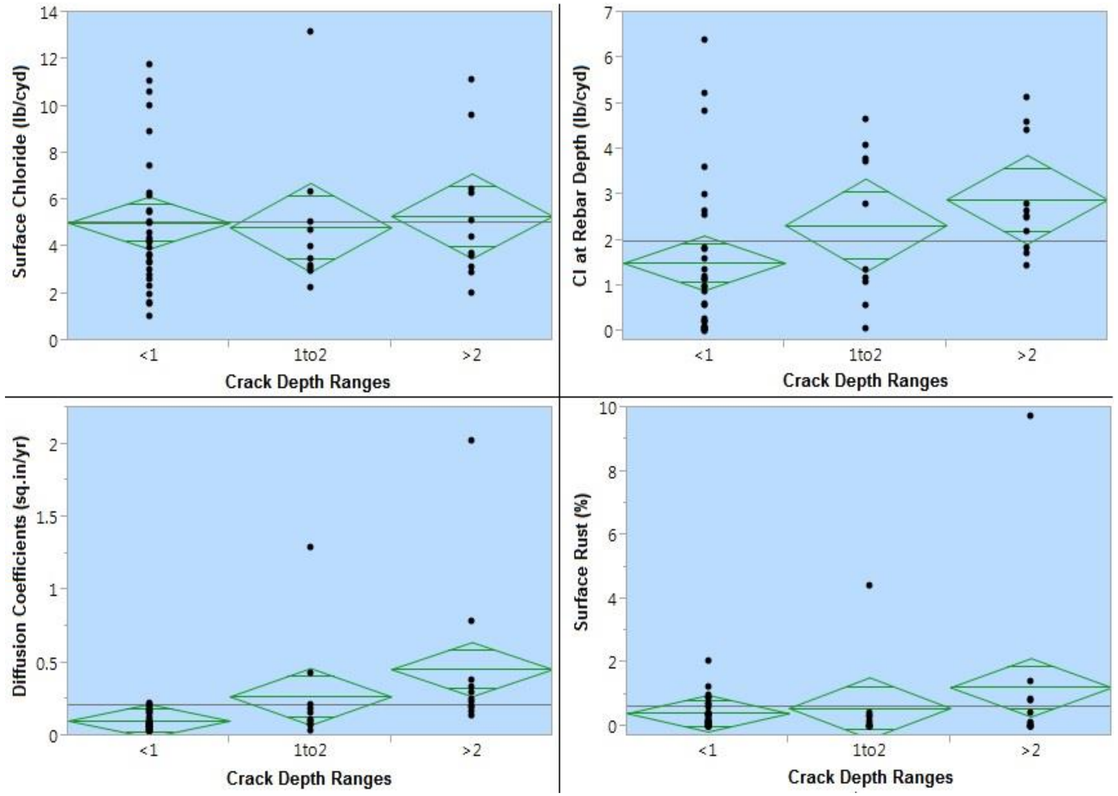




THRESHOLD OF CRACK DIMENSIONS

NO SCM



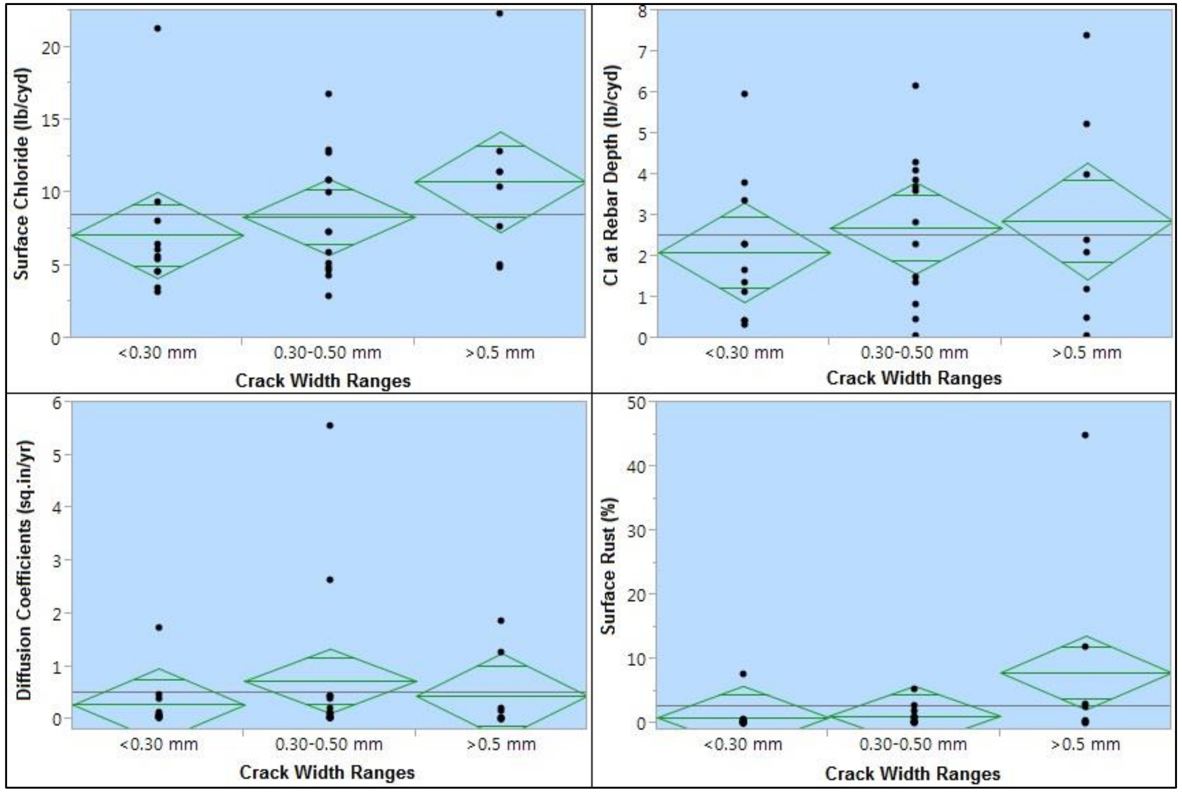


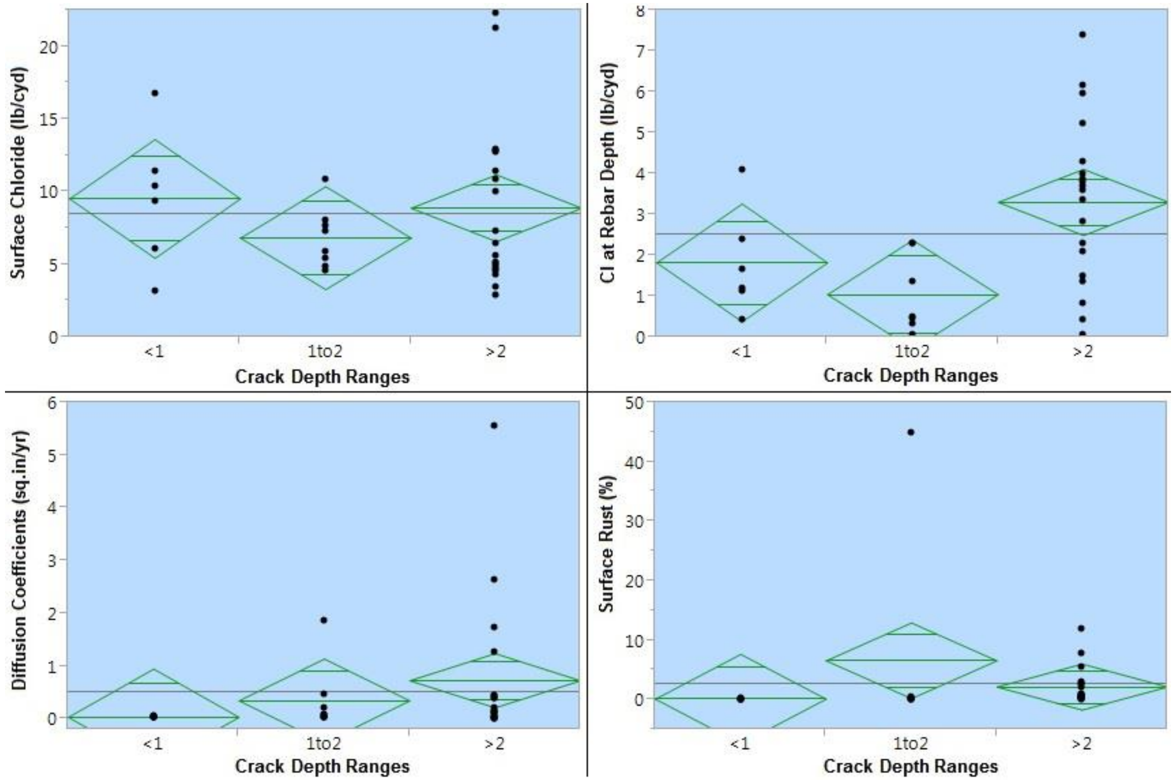
No statistical difference was found between crack width ranges

Statistical difference was found in diffusion coefficients and Chloride at Rebar Depth for the crack depth ranges

THRESHOLD OF CRACK DIMENSIONS

SCM

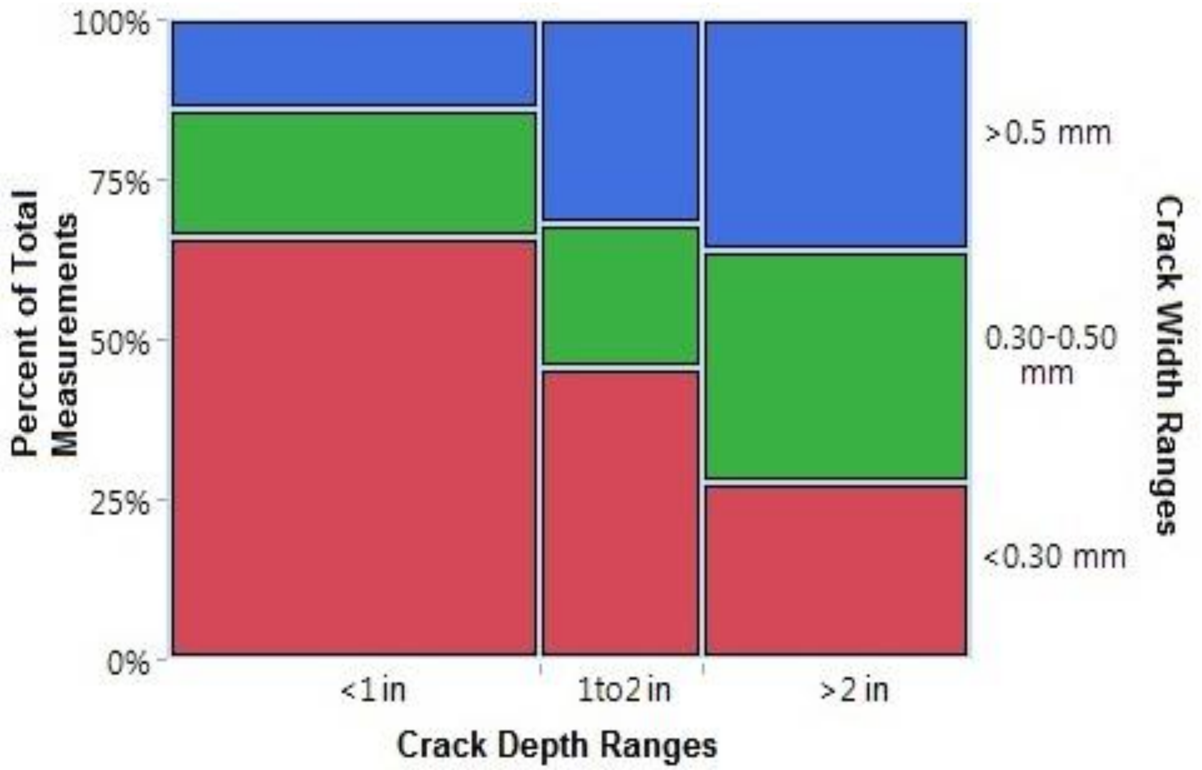


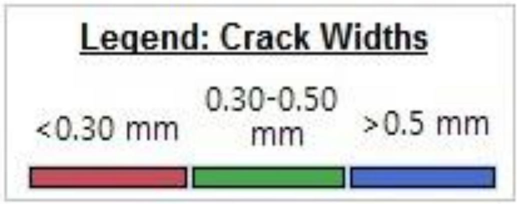


No statistical difference was found between crack width ranges

Statistical difference was found in Chloride at Rebar Depth for the crack depth ranges

CRACK WIDTH AND DEPTH CORRELATION





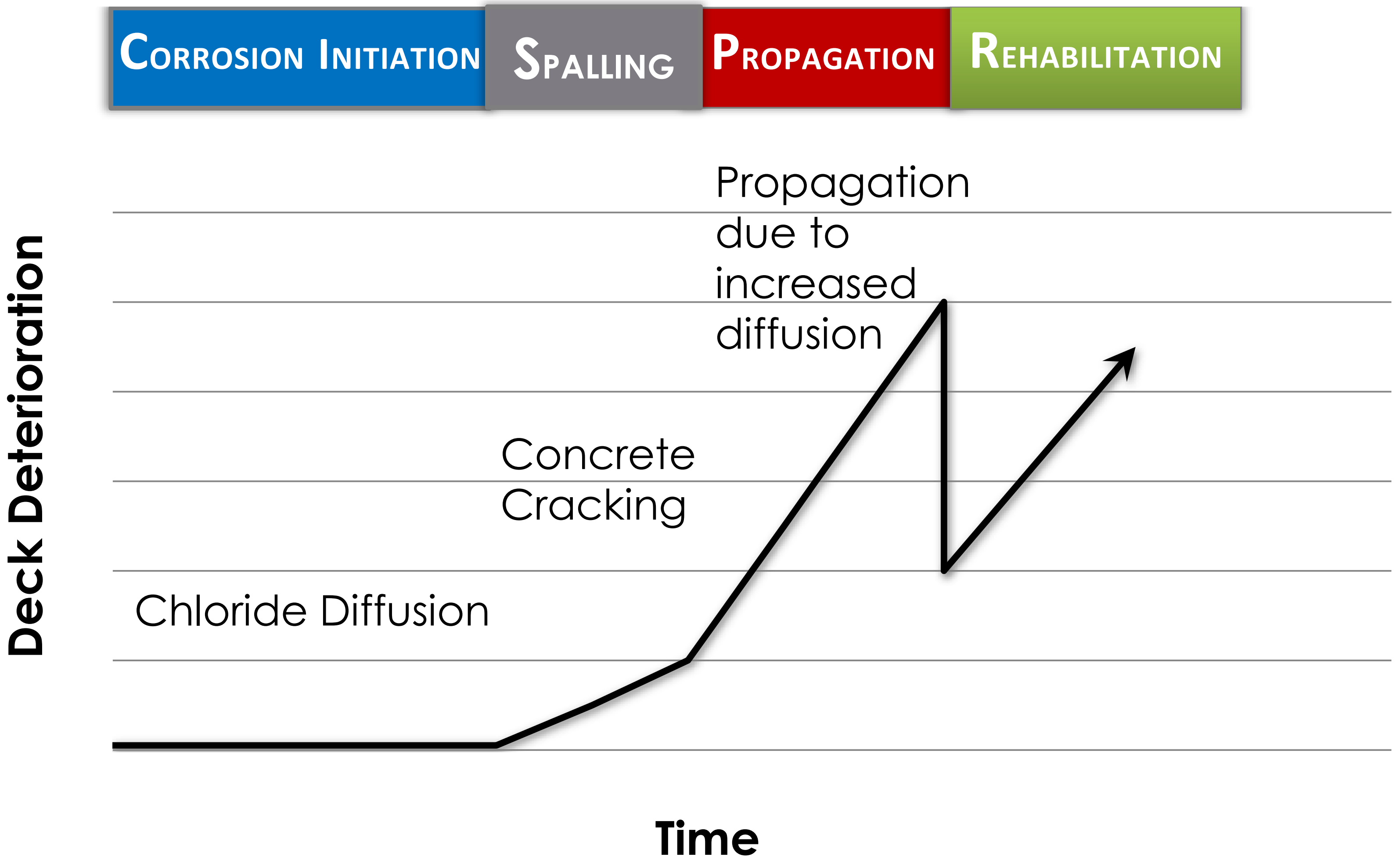
Test	ChiSquare	Prob>ChiSq
Pearson	13.116	0.0107*

H_0 = Crack Widths and Crack Depths are Independant

CONCLUSION (2 OF 4)

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

BRIDGE DECK DAMAGE CURVE



CORROSION SERVICE LIFE

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

Service Life of Bridge Decks

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

TIME TO CORROSION INITIATION - UNCRACKED CONCRETE & BARE REBAR

Groups	0.45 w/cm No SCM	0.45 w/cm SCM
	Uncracked (years)	Uncracked (years)
Time for corrosion initiation (0% to 2% Deck Damage)	8	28

DIFFUSION CLASSIFICATION

Cracked/ Uncracked	Crack Frequency	Diffusion at Cracks	Crack Influenced Deck Area and Number of Data			
			0.45 w/cm No-SCM (years)		0.45 w/cm SCM (years)	
			Freq, #	D_c in^2/yr	Freq, #	D_c in^2/yr
Cracked	Low Frequency	Low Diffusion	3%, 4	0.033 – 0.037	3%, 3	0.009 – 0.023
		Median Diffusion		0.110 – 0.136		0.081 – 0.095
		High Diffusion		0.386 – 1.297		1.748 – 2.651
Cracked	Median Frequency	Low Diffusion	9%, 14	0.033 – 0.078	7%, 6	0.009 – 0.025
		Median Diffusion		0.084 – 0.172		0.050 – 0.119
		High Diffusion		0.202 – 1.297		0.450 – 2.651
Cracked	High Frequency	Low Diffusion	25%, 46	0.033 – 0.386	15%, 14	0.009 – 0.059)
		Median Diffusion		0.036 – 0.428		0.031 – 0.202
		High Diffusion		0.037 – 1.297		0.126 – 2.651
Uncracked	--	--	137	0.0015 – 0.741	80	0.0015 – 0.897

TIME TO CORROSION INITIATION – CRACKED CONCRETE & BARE REBAR

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

A Triangular distribution with a minimum of 0.39, mode of 1.40, and a maximum of 6.26 lb/yd^3 was used as chloride threshold for corrosion initiation for bare rebar.

CONCLUSION (3 OF 4)

- Service life of 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.

VDOT SPECIFICATIONS
CORROSION RESISTANT REINFORCING STEEL

- **Class I** shall conform to ASTM A1035/A1035M
- **Class II** shall conform to AASHTO Designation: MP 13M/MP 13-04
- **Class III** shall conform to ASTM A955/A955M

CHLORIDE THRESHOLD FOR CRR

- ASTM A1035 Rebar:
  - Gerardo Clemeña (2003) reported 4.6 – 6.4 times bare rebar
  - David Darwin (2009) reported 4 times bare rebar
  - David Trejo (2004) reported 7.7 lb/yd^3 as opposed to 0.9 lb/yd^3

- ASTM A955 Rebar:
  - Gerardo Clemeña (2003) reported 10.4 times bare rebar

TIME TO CORROSION INITIATION – CRR

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+

CONCLUSION (4 OF 4)

- 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.

LIST OF 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.
- Service life of 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.
- 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

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Linear Cracking in Bridge Decks

http://www.virginiadot.org/vtrc/main/online_reports/pdf/18-r13.pdf

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Final Report VTRC 18-R13

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