


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Chloride Penetration Resistance and Link to Service Life Design of Virginia Bridge Decks

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

Presentation Outline

- Starting point: previous Virginia studies
- Objectives
- Data collection & characterization
- Investigations and findings
- Case study bridge evaluation
- Discussion and conclusions

Previous work

- Many relevant studies have been performed for VDOT
  - Deicing salt application
  - Chloride profiles
  - Cover depth measurements
  - Chloride migration coefficients (ASTM C1202-mod)
  - Service life predictions

- Other data sources
  - European literature
  - Florida DOT study: maturation/aging

Gaps

- Virginia-specific research did not use *fib*
- Data from other countries/states may not be applicable to Virginia
- Data collected 10-30 years ago: new low-cracking concrete not investigated

Objectives

1. Build on previous research to collect data to implement *fib* for VA low-cracking concrete decks

2. Investigate the importance of assumptions made in *fib*

3. Evaluate the service life and life-cycle cost for a case study bridge

Research plan

- Collect concrete mix data for all Districts and exposure data for 6 regions
- Collect and process results of previous studies
- Use reliability (probabilistic) methods to identify critical variables
- Perform more detailed analyses of critical variables
- Implement *fib* and LCC for Lynchburg bridge

Objective 1: data required

$$C(x,t) = C_0 + (\mathbf{C}_{\mathbf{s},\Delta\mathbf{x}} - C_0)\left(1 - erf\,\frac{a - \Delta x}{2\sqrt{\mathbf{D}_{\mathbf{app,c}} * t}}\right)$$

where,

C_0 = initial chloride concentration

$\mathbf{C}_{\mathbf{s},\Delta\mathbf{x}}$ = surface chloride concentration at depth equal to Δx

a = cover depth

Δx = depth of convection zone (transfer function)

$\mathbf{D}_{\mathbf{app,C}}$ = apparent diffusion coefficient

t = time

1. Data collection & characterization

Tasks:

a. Characterize chloride penetration resistances of concretes across Virginia ready mix suppliers

b. Characterize other concrete properties

c. Characterize exposure regions across Virginia

d. Characterize other model parameters

1a. Migration coefficient

Bridge (No. of Samples)	$D_{RCM,0}$ [mm^2/year]		Coeff. of Variation
	Mean	Std. Dev.	
Bridge #1 - Richmond (3)	139	25	0.18
Bridge #2 - Richmond (6)	620	67	0.11
Bridge #3 - Richmond (6)	479	63	0.13
Bridge #4 - Bristol (3)	703	28	0.04
Bridge #5 - Bristol (6)	567	206	0.36
Bridge #15 - Richmond (3)	285	48	0.17
Bridge #16 - Richmond (6)	197	106	0.54
Bridge #17 - Lynchburg (9)	467	59	0.13

Variation in the variation

1b. Other concrete data

$$D_{app,C} = k_e \, D_{RCM,0} \, k_t \, A(t)$$

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right) \qquad A(t) = \left(\frac{t_0}{t}\right)^{a}$$

where,

k_e = environmental transfer parameter

b_e = regression variable

T_{ref} = standard reference temperature

T_{real} = ambient temperature

$D_{RCM,0}$ = chloride migration coefficient

k_t = transfer parameter

$A(t)$ = aging sub-function

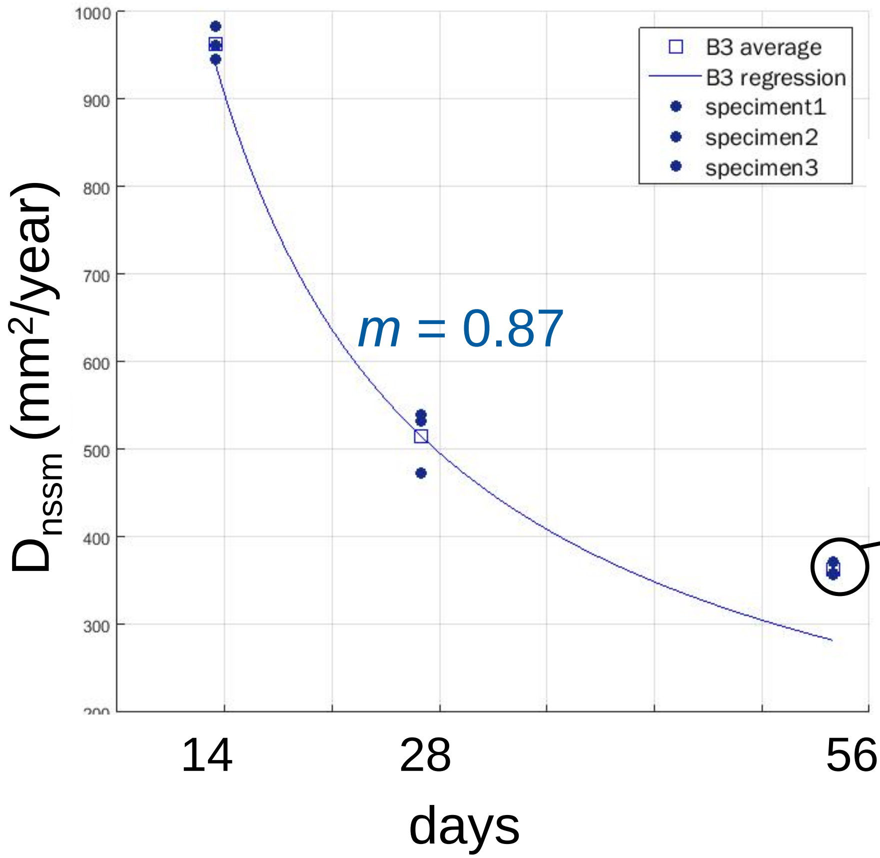
α = aging coefficient

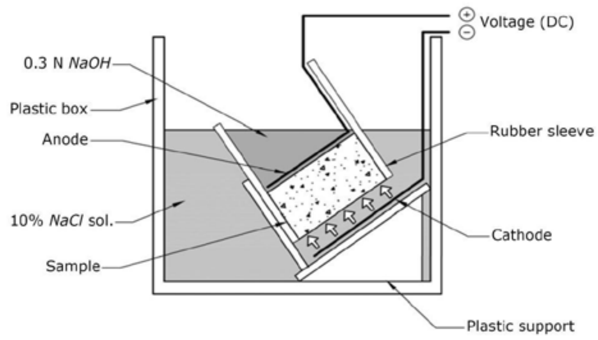
t_0 = reference time (28 days)

t = time

1b. Maturation coefficient

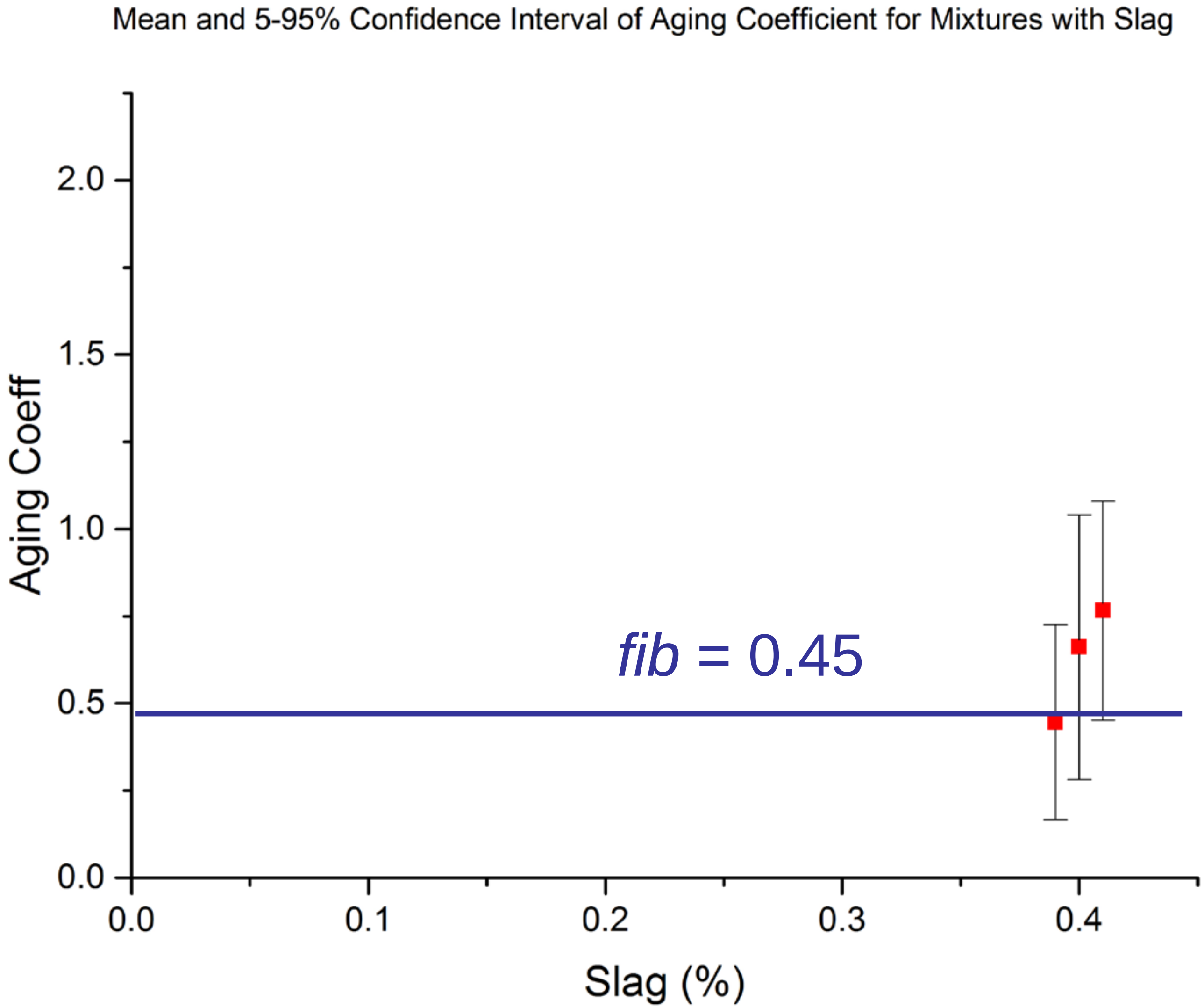
$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m$$



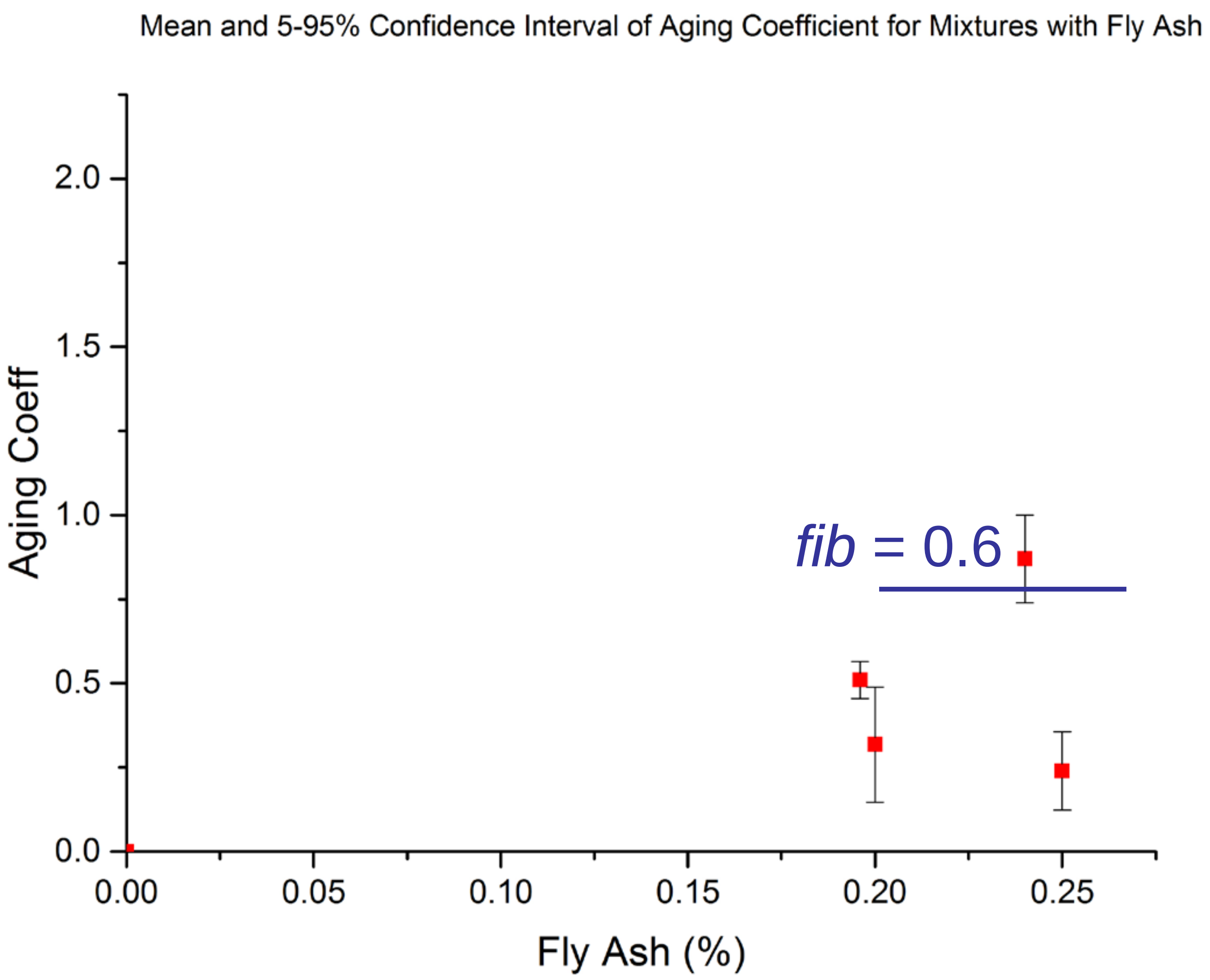


NT Build 492

1b. Maturation coefficient



1b. Maturation coefficient



1b. Sample data

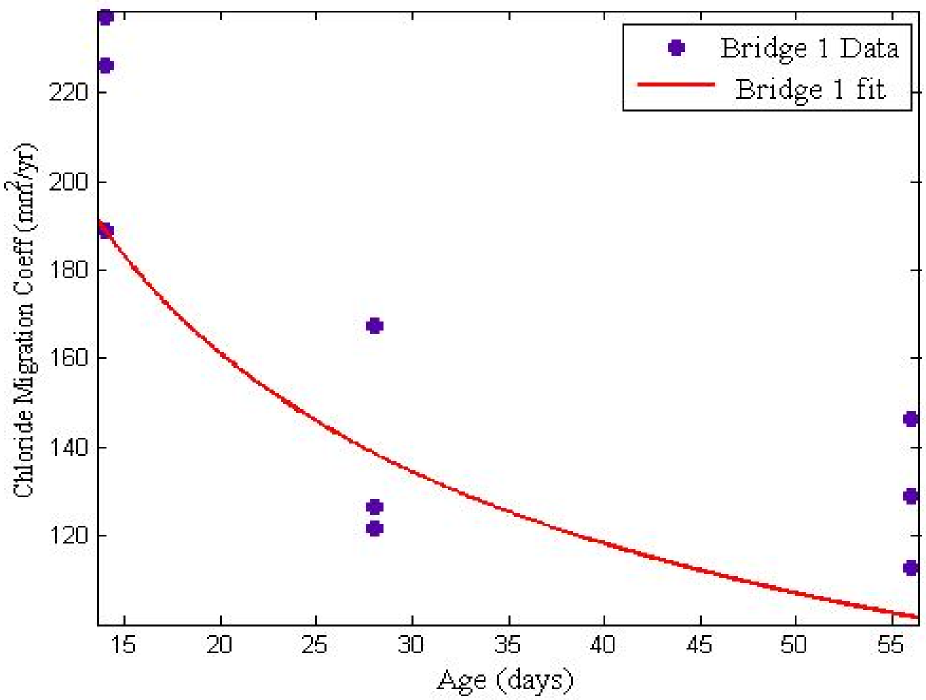
Concrete

Producer	Vulcan Materials Co.
Mix Design (0.45 w/c)	Type 2 Cement + 40% Slag

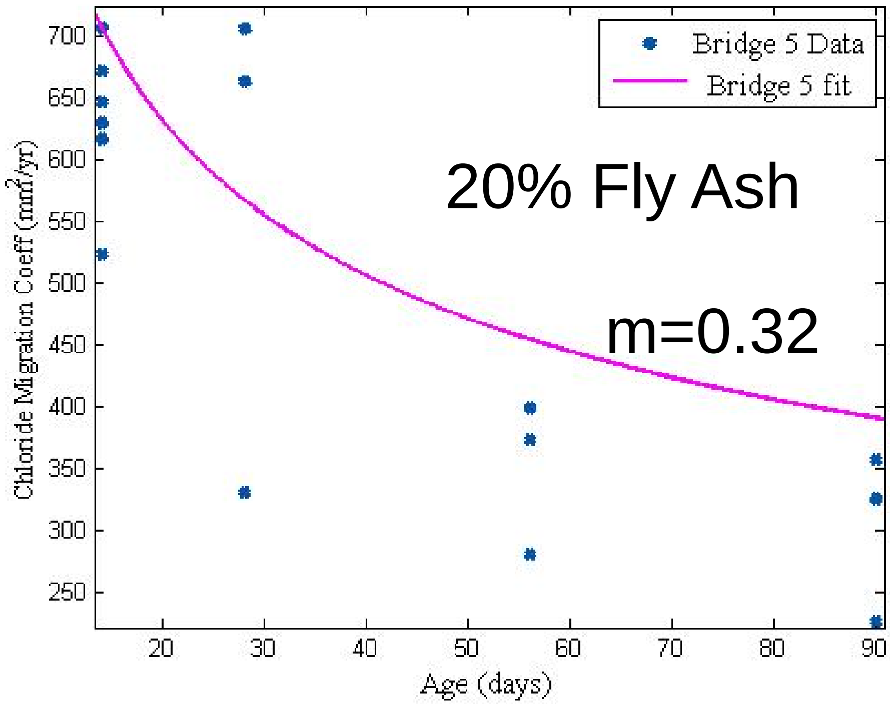
Concrete Characteristics (from tests)

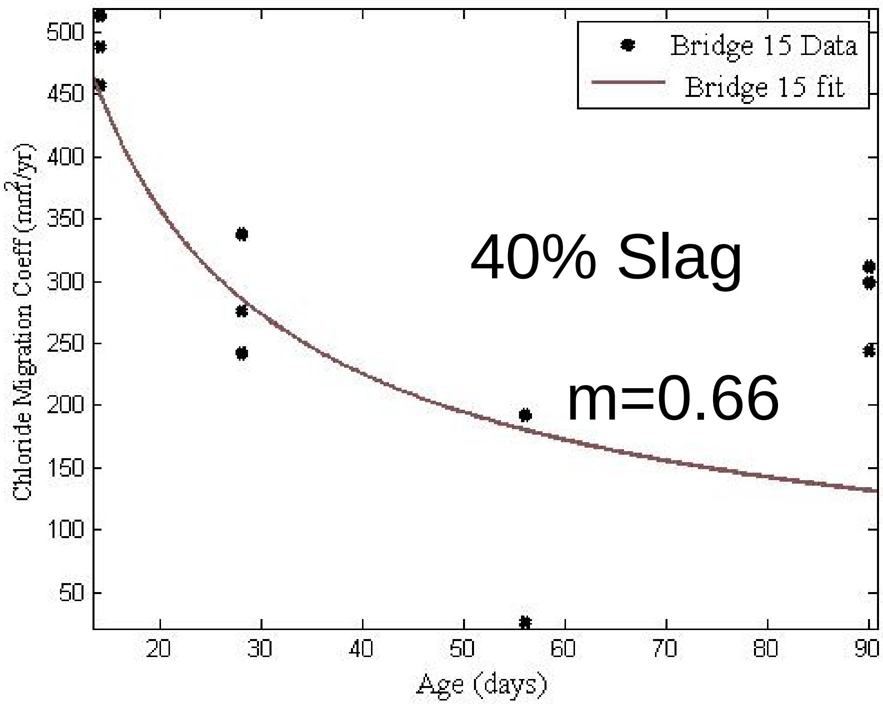
Mean Initial Chloride Content *[from chloride titrations]*	0.034% wt. cl/ wt. binder
Mean 28 day Chloride Migration Coefficient *[from NT Build 492 Test]*	138.6 mm^2/yr
Aging Coeff. (α) *[from curve fitting]*	0.45

$D_{RCM,0}$ v/s Concrete Age



1b. Sample data





AGING ≠ MATURATION

1b. Other concrete properties

- Initial chloride concentration:
  - VDOT/VTRC performed titration on 4 bridges
  - Compared with prior results; agreement

- Temperature correction coefficient, b_e: use *fib*

1c. Exposure data

Chloride concentration: two options:

– Survey data

– *fib* equation

$$C_{eqv} = C_{0,R} = \frac{n \cdot c_{R,i}}{h_{s,i}}$$

where,

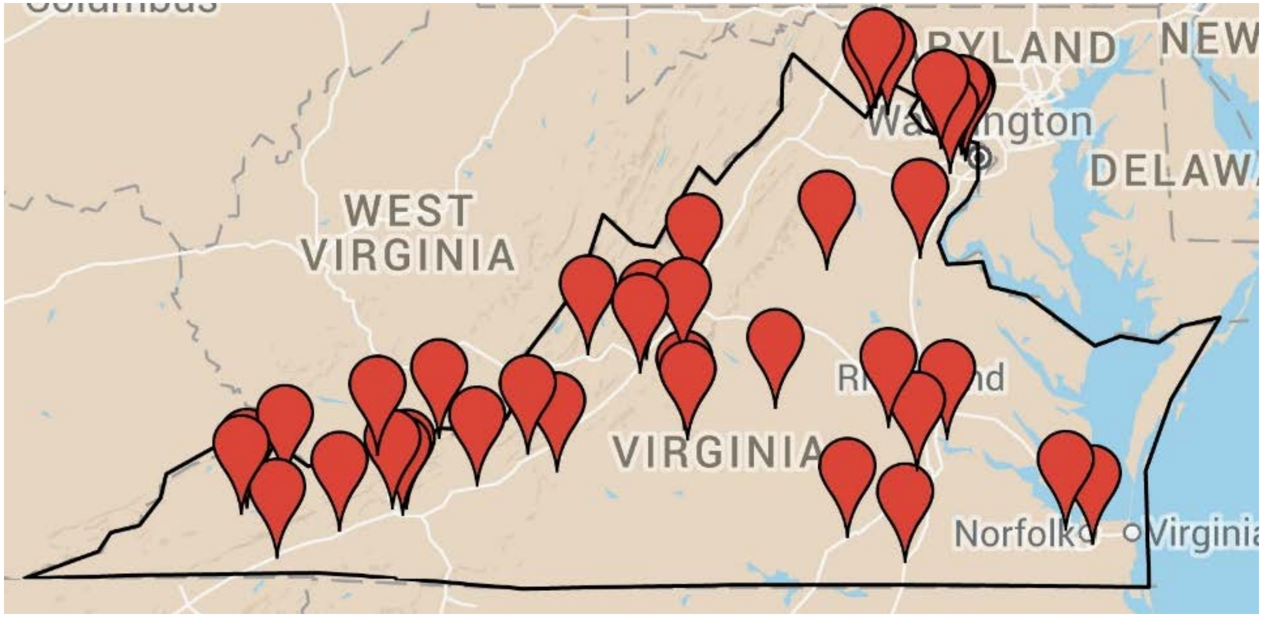
$c_{0,R}$ = avg. chloride content of chloride contaminated water (g/l)

$c_{R,i}$ = avg. amount of chloride per salting event (g/l)

n = average number of salting events per year

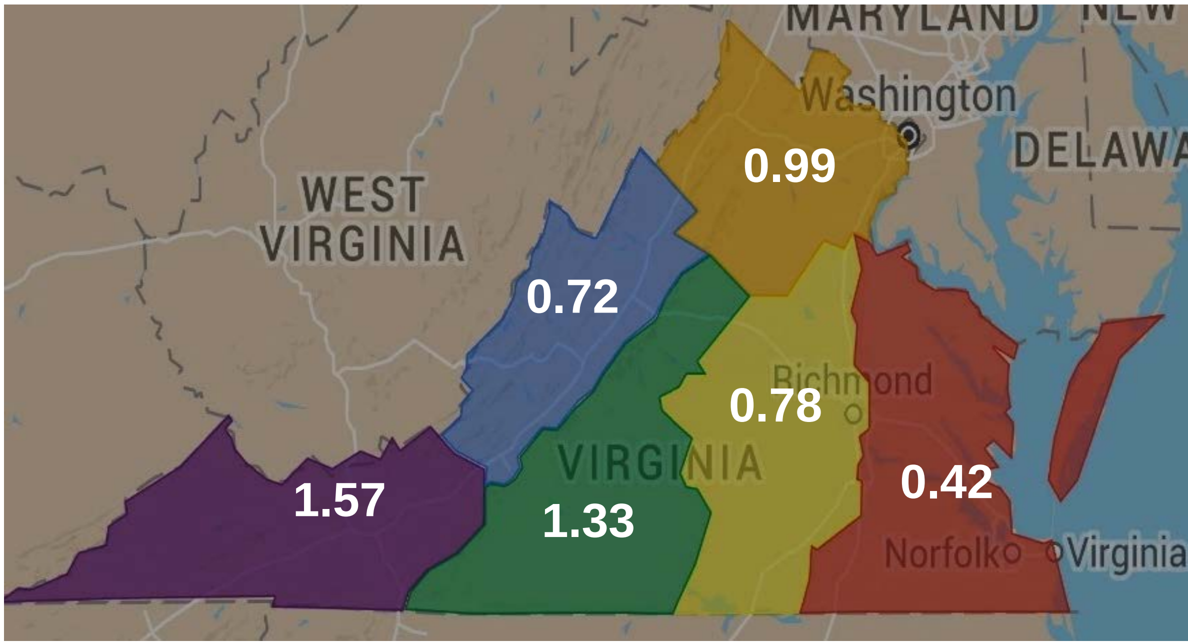
$h_{S,i}$ = amount of water from rain and melted snow per spreading period (l/m²)

1c. Surveyed chloride profiles



- Data from Kirkpatrick 2001; Williamson 2007
- Most mixes contained supplementary cementitious materials
- Anti-icing/deicing practices have changed

1c. Surveyed data



Color	Region
	Tidewater
	Northern
	E Piedmont
	W Piedmont
	Central Mountain
	SW Mountain

$$\left(\% \frac{\text{mass Cl}}{\text{mass binder}}\right)$$

1c. *fib* chloride model

Assume: Salting event assumed to occur if:
Snow > 0”
20 °F < Temp < 32 °F

Data: Williamson (2007) collected data on the volume of deicing salt used in each District / lane mile

$$C_{eqv} = C_{0,R} = \frac{n \cdot c_{R,i}}{h_{s,i}}$$

Known: concentration of brine

Data: temperature, snow, rain, across region for 30 years

Model: equation relating snow to liquid water

1c. *fib* chloride model

Region	*n*, salting events/ year	$C_{R,i}$, chloride spread/ year, $\frac{g}{m^2}$	$h_{s,i}$, amount of water, mm	C_{oR}, chloride concent. of contaminated water, $\frac{g}{l}$
Tidewater	12	38	221	0.18
E Piedmont	11	90	133	0.69
W Piedmont	12	37	238	0.16
Northern	**29**	**742**	**223**	**3.32**
Central Mountain	37	114	253	0.45
SW Mountain	42	117	285	0.30

1c. *fib* chloride model

Still need to translate to surface chloride concentration in the concrete…

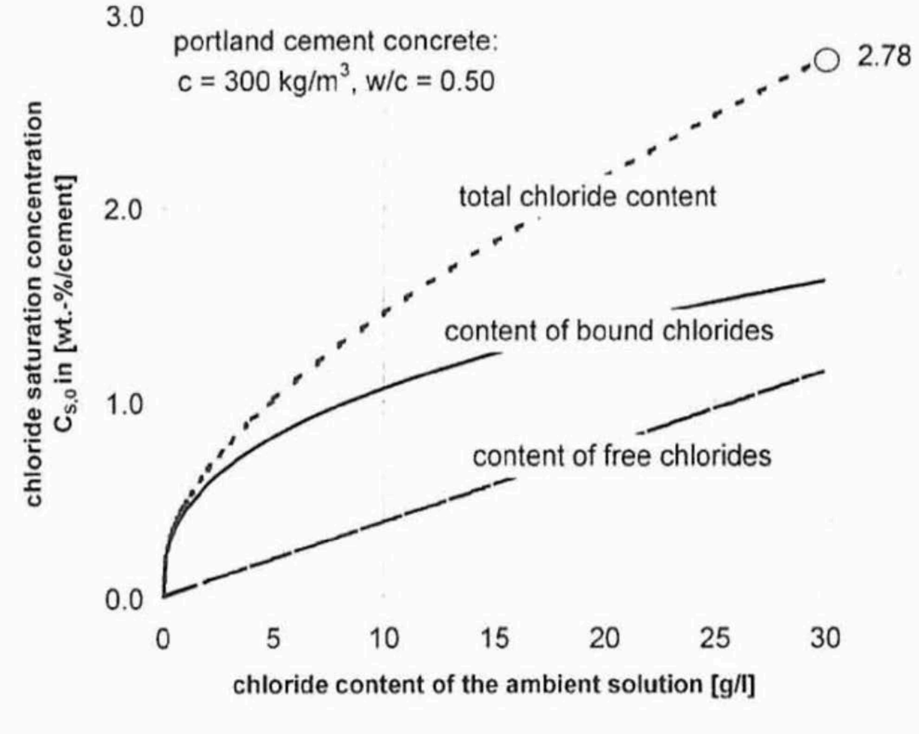
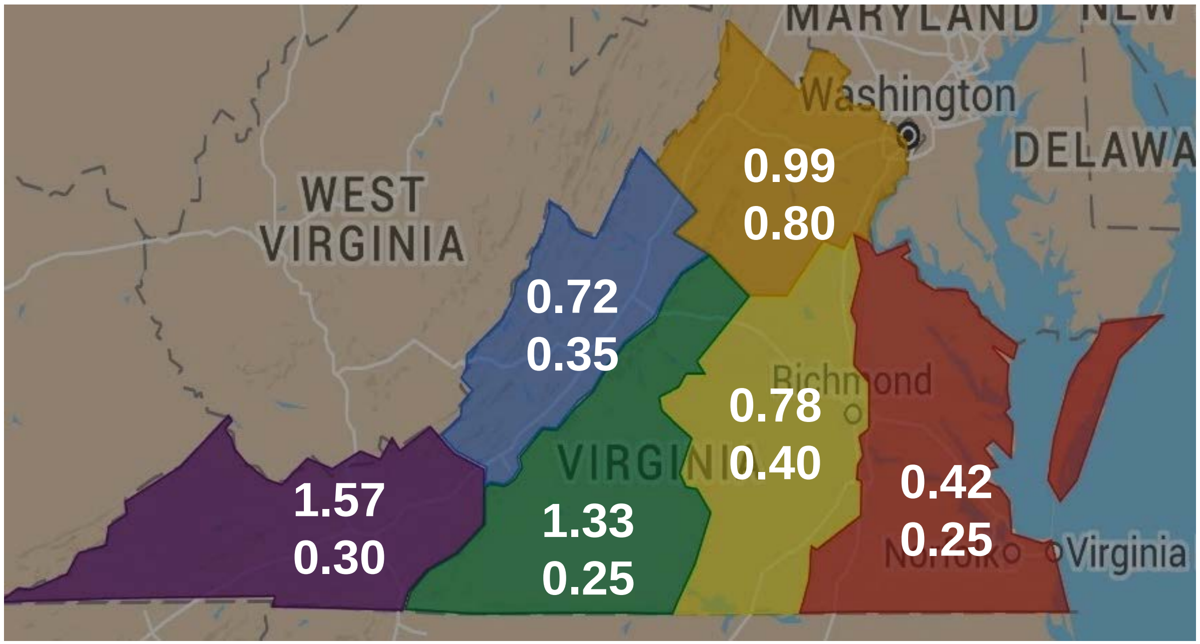


Figure B2.2-2: Surface chloride concentration $C_{S,0}$ in dependency on C_{eqv} for a Portland cement concrete

1c. Comparison



$(\% \frac{\text{mass Cl}}{\text{mass binder}})$

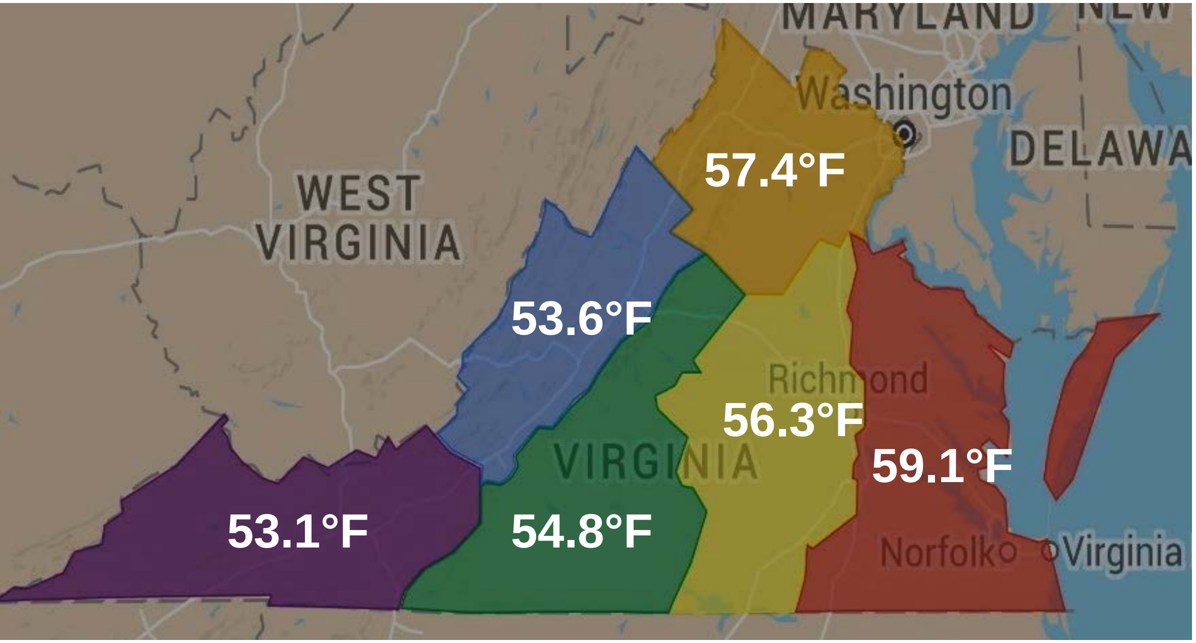
---- Historical data

---- *fib* predicted

- Same order of magnitude
- *fib* significantly lower
- Highest: SW Mountain (survey), Northern (*fib*)

Color	Region
	Tidewater
	Northern
	E Piedmont
	W Piedmont
	Central Mountain
	SW Mountain

1c. Temperature characterization



Color	Region
	Tidewater
	Northern
	E Piedmont
	W Piedmont
	Central Mountain
	SW Mountain

- 1985-2015 data
- Annual mean, standard deviation
- >70 stations

1d. Other data

Variable / Material		Distr.	Mean	Std. Dev.	Lower Limit	Upper Limit	Source
Cover depth (a) [mm]		Log-normal	Nom.	8	-	-	*fib* (2006)
Transfer Function (Δx) [mm]		-	12.7	-	-	-	Cady & Weyers (1983)
Critical Chloride Concentration, C_{crit} [% wt. binder]	Plain Steel	Beta	0.65	0.15	0.2	2	*fib* (2006)
	MMFX Steel	Log-normal	1.08	0.443	-	-	Ji et al. (2005)

- Cover depth: mean is probably biased against nominal
- Transfer: ideally would include uncertainty
- Data format precluded generation of these parameters

1. Main Findings

- Leverage existing data and new work to characterize all parameters needed to implement *fib*

- Ideally would have more data for some parameters
  - Aging
  - Surface chloride concentration
  - Transfer function
  - Cover depth

2. FURTHER INVESTIGATIONS

a. Sensitivity assessment
b. Evolution over time: aging, delays, etc.
c. More on surface chlorides

2a. Sensitivity assessment

- Analysis of the **limit state** equation for depassivation of reinforcement:

$$g(\mathbf{X}) = \underbrace{C_{crit}}_{\text{equivalent resistance}} - \underbrace{\left(C_0 + (C_{s,\Delta x} - C_0)\left(1 - \operatorname{erf}\frac{a-\Delta x}{2\sqrt{D_{app,c} * t}}\right)\right)}_{\text{equivalent load}}$$

- Use the First Order Reliability Method
- Uncertainty in all variables considered jointly

2a. Sample sensitivities

Variable Rank	Importance Factor (γ)
α	**-0.62**
C_{crit}	-0.53
$C_{s,\Delta x}$	**0.46**
T_{real}	0.28
a (cover)	-0.17
$D_{RCM,0}$	0.11
C_0	0.04
b_e	-0.003

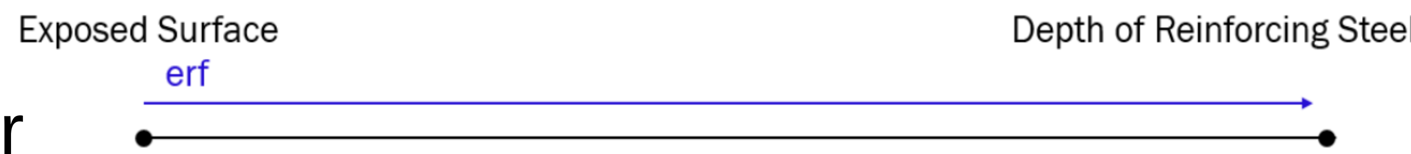
2a. Trends in sensitivities

- α most important, followed by $C_{s,\Delta x}$, and T_{real} or C_{crit}

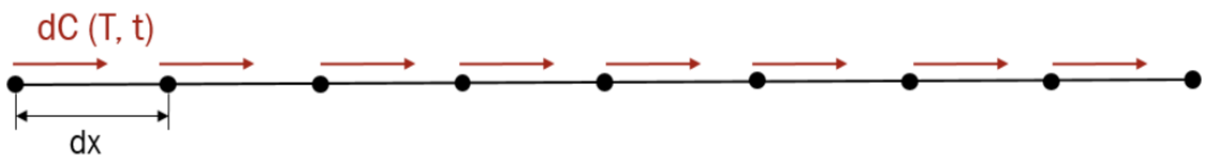
- Findings agreed with literature and a previous uni-variate study

2b. Evolution in time

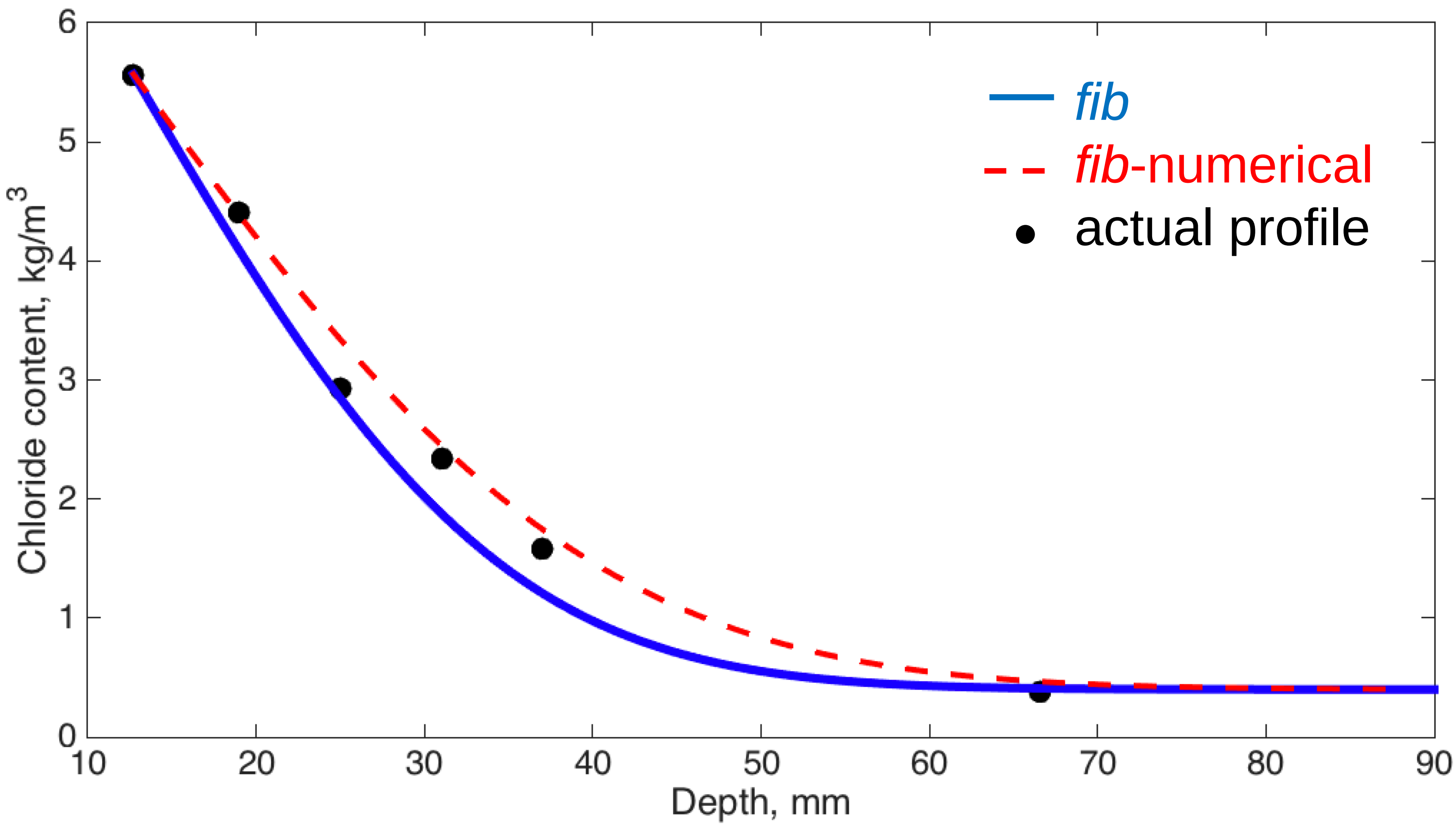
fib uses error function approximation



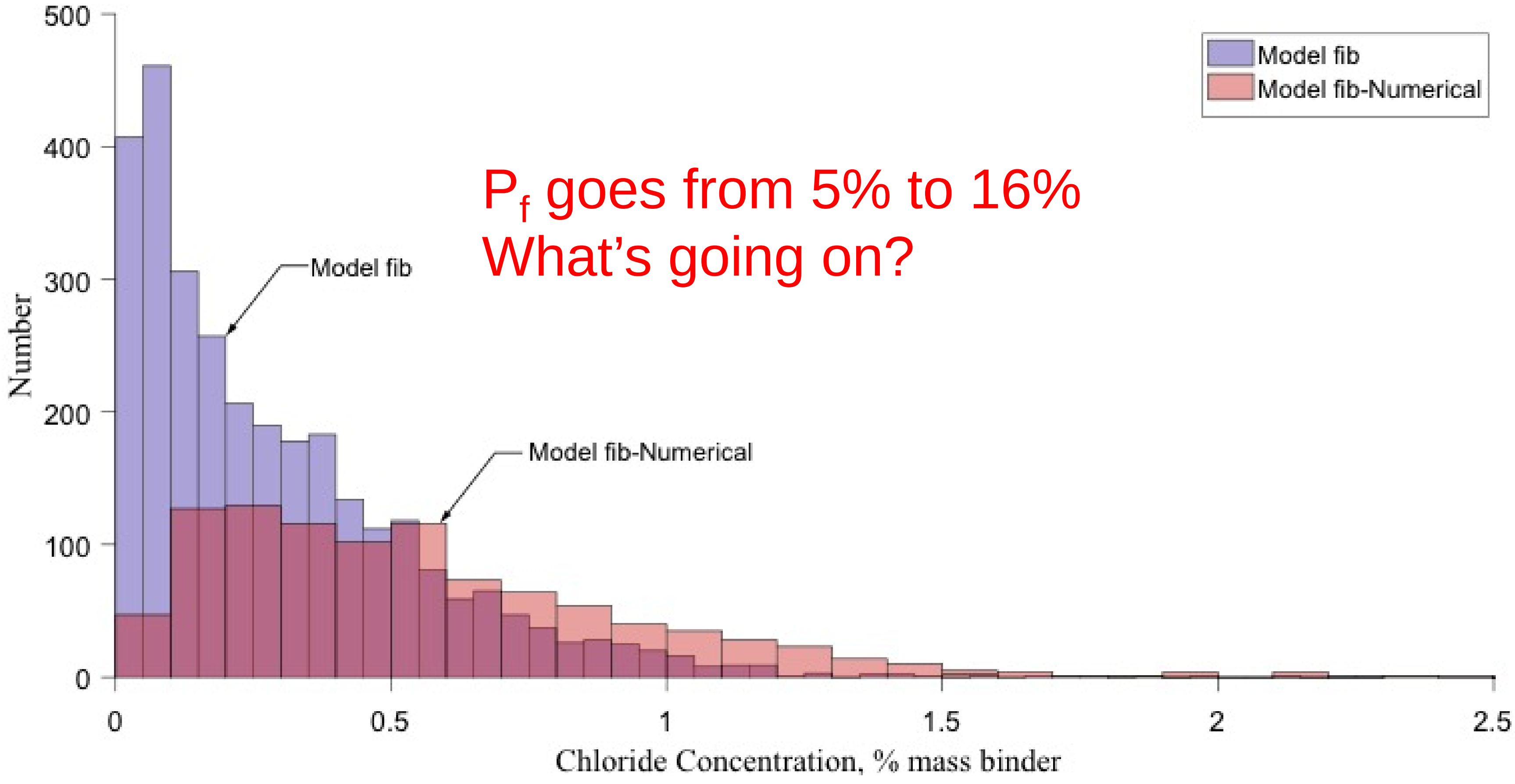
fib-numerical solves diffusion by taking finite steps in time and space



2b. Solution method



2b. Sample numerical results

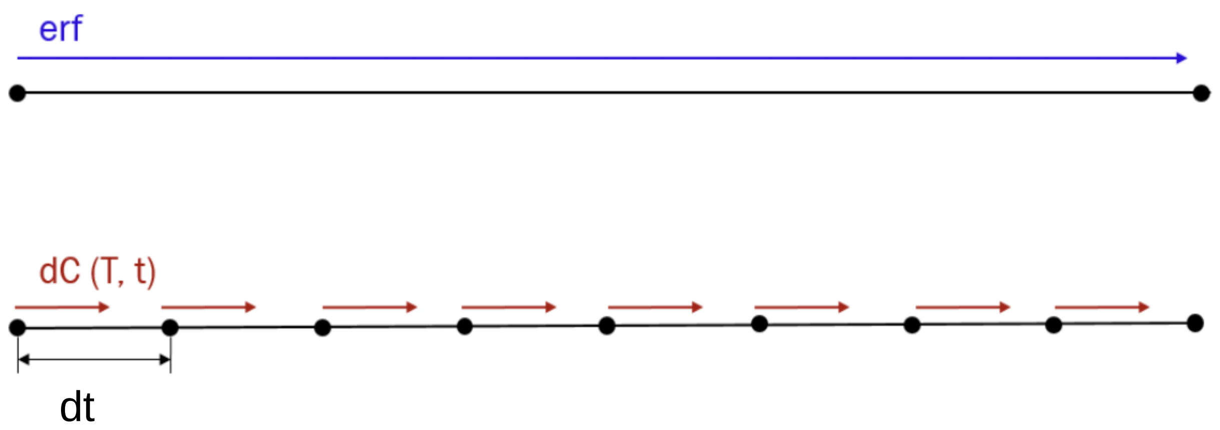


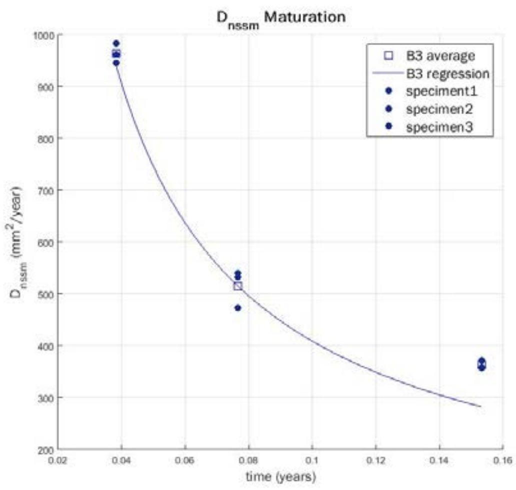
P_f goes from 5% to 16%

What's going on?

2b. Aging is the culprit

Aging coefficient best predictor of difference between error function and numerical results

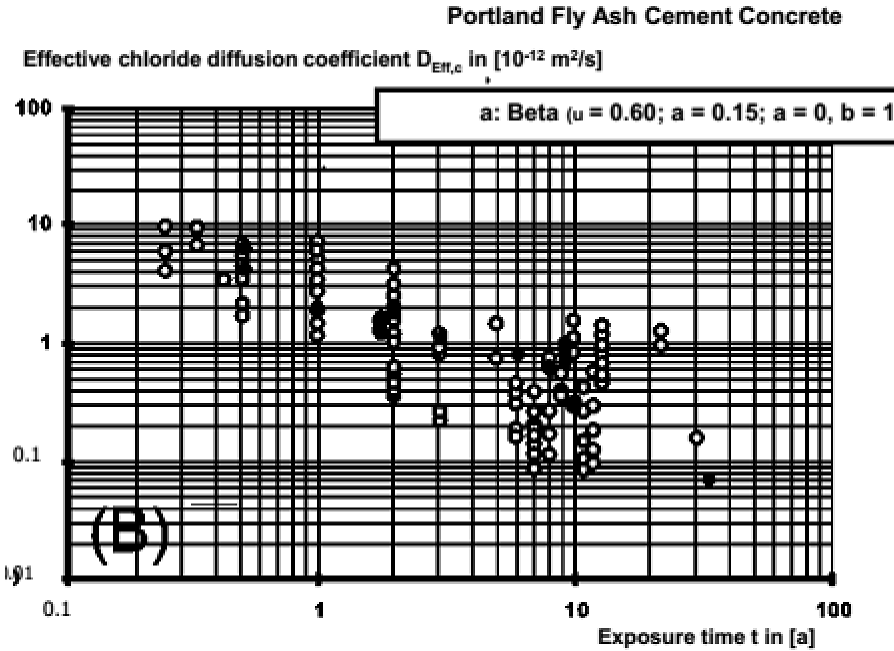




2b. What is aging?

Aging coefficient combines all time-based effects, e.g.:

- Curing
- Binding
- Changes in surface chloride concentration



The *fib* data came from surveys of existing (European) structures:

- Cores were taken at <1 to 20+ years
- The maturation curve was forced through the 28-day value for *fib*'s estimate based on the mix design

2b. What to do?

- Use aging values provided by *fib*
- Don’t use numerical solutions unless α was obtained consistently (not done)
- Need more data:
  – NT-Build: bridges from this study, existing bridges
  – Diffusion: need 1-2 years of data

2b. Other evolutions

Time-dependent surface chloride functions

- **Literature:** a linear ramp function decreased P_f by about 1 - 2% (e.g., from 3.4% to 2.4%)

- **Numerical model**: Delaying time to first exposure also decreased P_f by 1 - 2%

Time to first exposure	$\mathbf{P_f}$
0 months	**0.23**
1 month	0.23
2 months	0.22
…	…
12 months	**0.21**

2c. Surface chlorides

- FORM sensitivity of *fib* chlorides model:
  - *n*, the number of salting events most important
  - $C_{s,i}$, chlorides spread, 2nd
- Deicing procedures and types have changed
- Limited data used (1-3 years)

2. Main findings

- Best to stick with *fib* error function approach
- Use surveyed data for surface chlorides
- More research is needed!

2. Sample data produced

Bridge #2: Richmond District (Rte. 712 over North Meherrin River)

Model fib

P_f 0.10% ***(Default run* – MMFX)***	P_f 0.60% *(Default run* – plain steel)*	P_f 0.26% *(FEM-estimated)**
P_f 0% *(Surface chlorides obtained from fib method)*	P_f 0% *(Ramp-type function for surface chlorides)*	**P_f 2.40%** ***(Aging coeff from curing)***

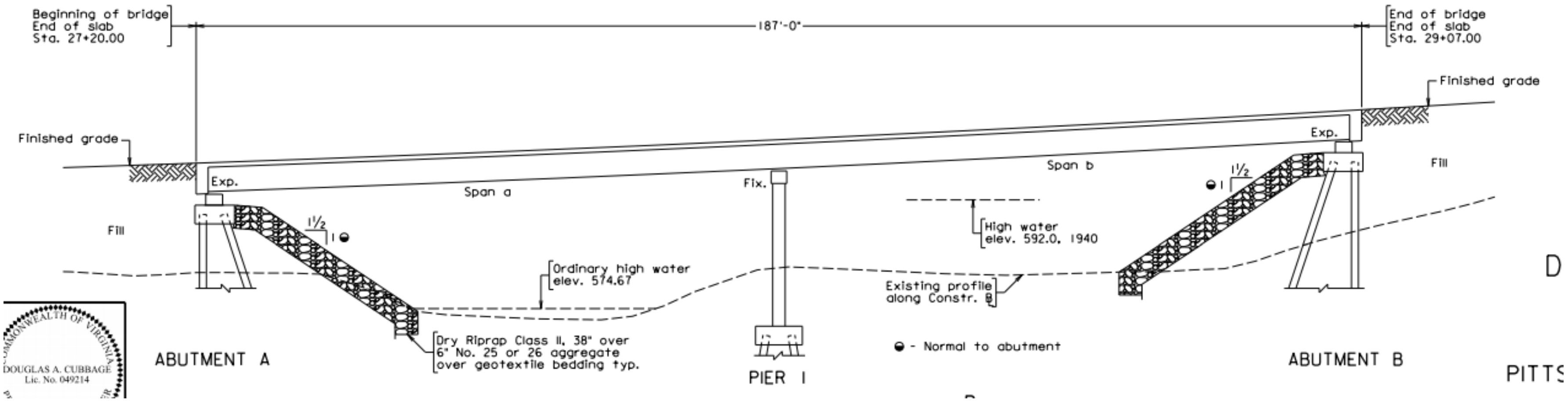
Model fib-numerical

P_f 1.08% ***(Default run – MMFX)***	P_f 4.34% *(Default run – plain steel)*
P_f 0.64% *(12 mo. delay to time to first chloride exposure)*	

- *DEFAULT RUN: simulations were run using fib-defined aging coefficients and constant surface chlorides from historical data. All other simulations run using Ccrit for MMFX steel*
- *NUMERICAL-ESTIMATED: obtained by multiplying the Pf from the default run by a factor based on aging coefficients to mimic the numerical model*

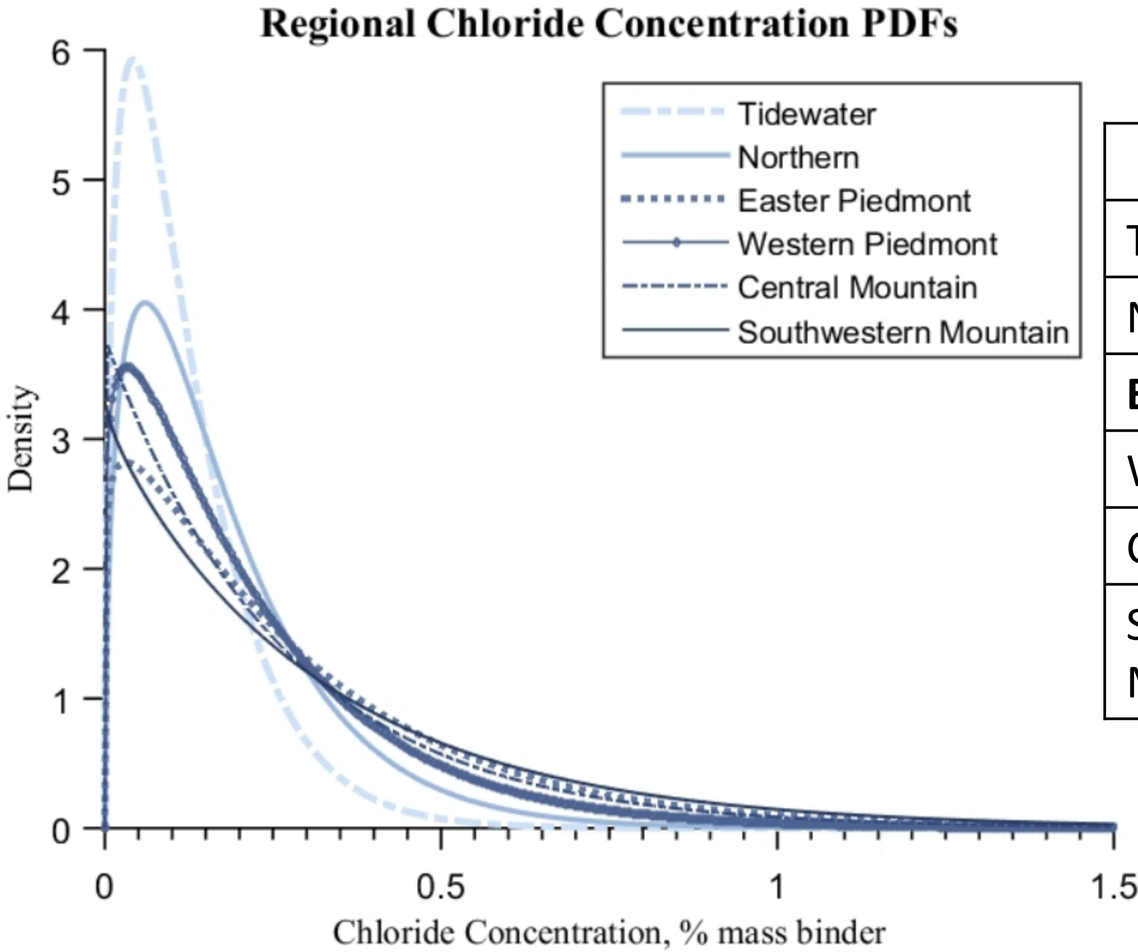
3. CASE STUDY

3. Lynchburg case study



- Data from the first bridge tested, supplemented from other bridge data
- Assumed bridge located in different regions
- Life-cycle costing for MMFX and plain steel

3. Influence of bridge location



Region	Pf
Tidewater	0.004
Northern	0.005
Eastern Piedmont	**0.047**
Western Piedmont	0.022
Central Mountain	0.047
Southwestern Mountain	0.071

Figure 16: Probability density functions for chloride concentration at the depth of reinforcing steel after 100 years for case study bridge in all Virginia exposure regions

3. Main findings

- Probability of failure acceptable (4.7%)
- Different design requirements for regions
- MMFX a good choice from life-cycle cost perspective

DISCUSSION AND CONCLUSIONS

Recap

- Possible to implement the *fib* Bulletin 34 method for service life design in Virginia
- Questions remain about critical variables (aging coefficient and surface chloride concentration)
- Low-cracking concrete and corrosion-resistant rebar (+ appropriate cover depths) can achieve 100-year service life

Research directions: aging

Option	Pros	Cons
Re-test bridges from this project (NT-Build)	all low-cracking concrete; already thoroughly characterized	only data for 1-2 years of exposure
Re-test older bridges (NT-Build)	have data at 12-35 years service; could at +10 years	not many non-OPC bridges left/able to test (not enough data)
Test new low-cracking concrete mixes (diffusion)	all low-cracking concrete; closest to real mechanism	Need to wait for 1-2 years
Use other data (e.g., chloride profiles from Balakumaran)	No new tests needed	No clear methodology

Research direction: chlorides

Goals:

- Update and improve data for Virginia
- Provide guidance to other states looking to collect this data and use *fib*

1. Re-collect data on de/anti-icing salt usage (with more details)

2. Perform ponding tests to link surface and pore concentrations

Big picture

- “If you can’t ~~measure~~ predict it, you can’t improve it”
- Accuracy of method can only be assessed with time
- Advantages of reduced early-age cracking not accounted for in *fib* (and most other) models

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Thank you!

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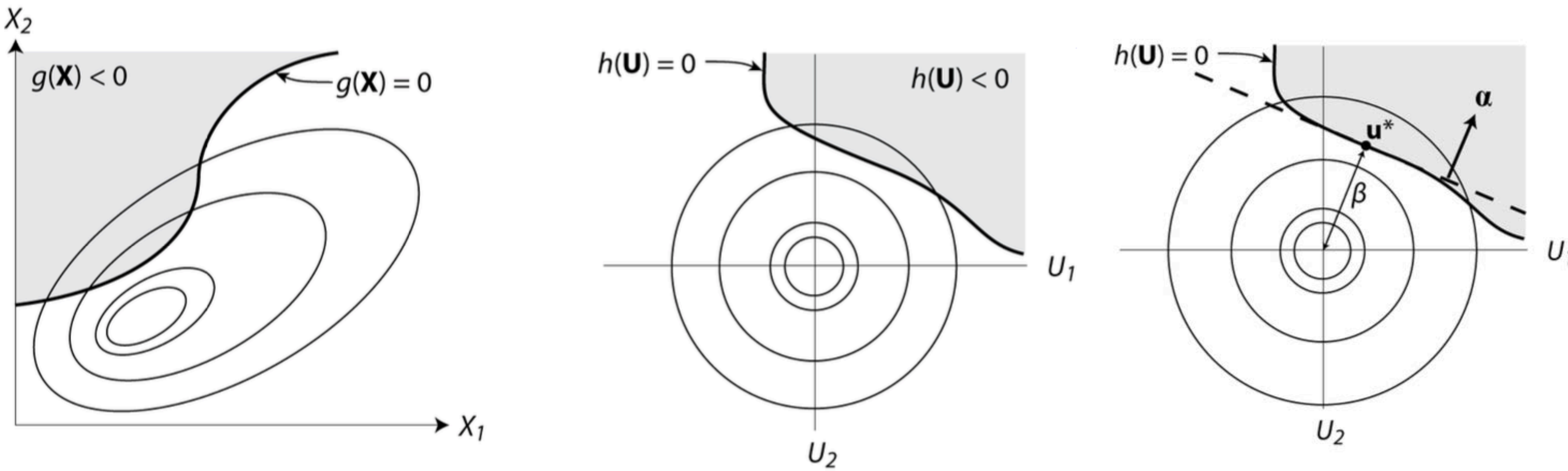
2a. First Order Reliability Method



$$p_f = \iiint_{g(\mathbf{X})\le 0} f_{\mathbf{X}}(\mathbf{x})d\mathbf{x}$$

$$p_f = \iiint_{h(\mathbf{U})\le 0} \phi_{\mathrm{U}}(\mathbf{u})d\mathbf{u}$$

$$p_f = \Phi(-\beta)$$

Data findings

- Variability of the 28-day migration coefficients were highly variable by supplier
- Maturation rates obtained from 14-28-56-(90)-day curve fits were very similar to those reported in *fib* for mixes containing fly ash and slag
  - This is despite *fib*'s background literature suggesting that maturation coefficients are not affected by early curing
  - We recommend the use of *fib* values in the absence of additional data
- More recent data could improve estimates of surface chloride concentration
  - Anti-icing/de-icing data and tests to link surface and pore concentration
  - Updated surveys
- All 8 bridges with full test results available had acceptable probabilities of failure using the default *fib* model and MMFX

Deliverables

- Excel spreadsheet and documentation for implementing the *fib* model, covering:
  - Six exposure zones using surveyed surface chloride concentrations and the fib method for deicing salts
  - Diffusion and maturation coefficients based on regions and mix type (from testing)
  - VDOT-specific distributions for transfer coefficients, cover depth, etc.
  - MMFX, stainless, and plain reinforcement

- "Factors" for estimating more advanced effects, such as:
  - Use of finite element models
  - Delay in time to first exposure
  - "Ramping up" of surface chloride concentrations

- Summary sheets of data related to the individual bridges tested