VTRC
Virginia Transportation Research Council

We bring innovation to transportation.

Virginia's Implementation of Service Life Design Concepts

SHRP2 R19A Workshop
International Bridge Conference

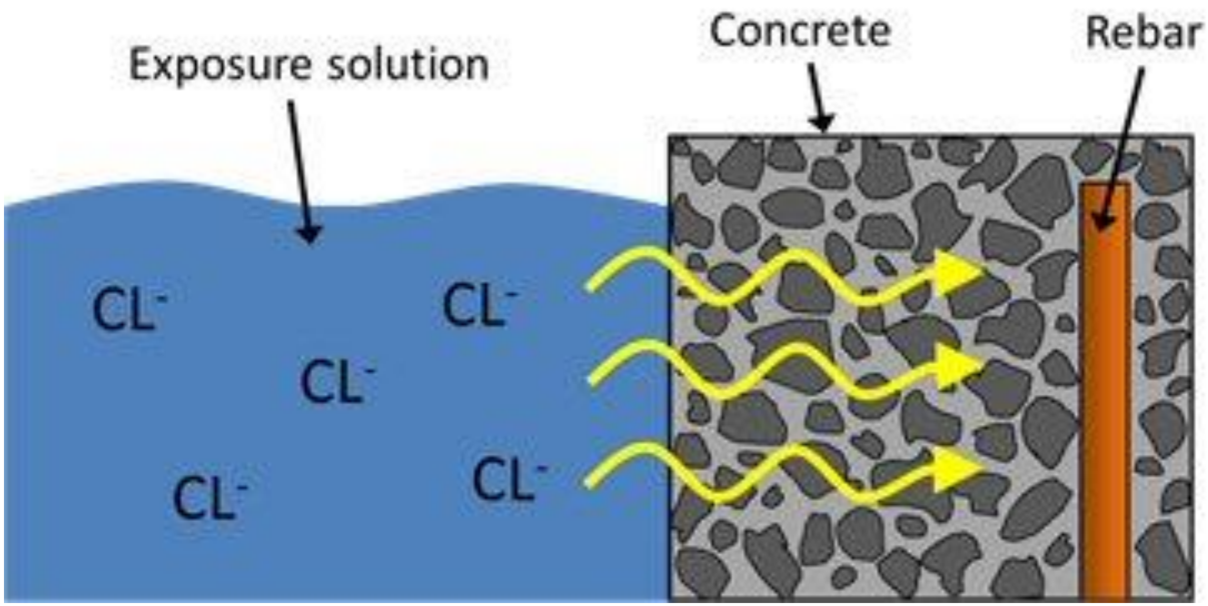
Presented by:
Michael C. Brown, Ph.D., P.E.
June 7, 2016

SHRP2-R19A
Design for 100-Year Service Life

Virginia's Goals:

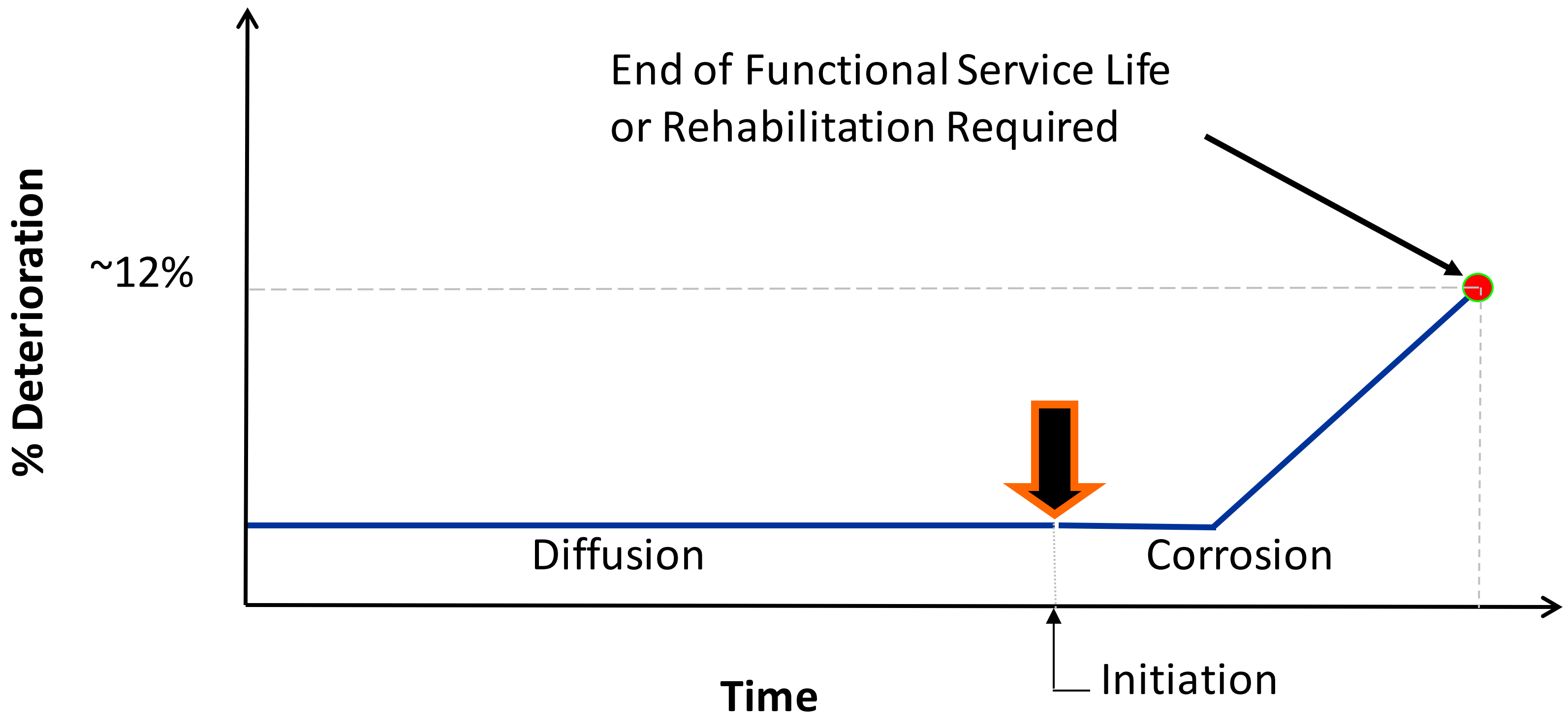
- Consider proposed methods to model for service life design
- Demonstrate how models can be used to support decision-making in design
- Develop a database of reference values specific to Virginia for use in modeling

Chloride Ingress



(Schematic Illustration of Chloride Ingress)

Chloride-Induced Corrosion



- Time to Initiation: Chloride Diffuses until Corrosion Begins
- Propagation Time: Time from Initiation to Accumulated Cracking and Spalling of Concrete

Chloride Ingress Modeling

Fick's 2nd Law

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left\{D\,\frac{\partial C}{\partial x}\right\}$$

where:
$C =$ ionic (chloride) concentration
$D =$ proportionality (diffusion) constant
$t =$ time
$x =$ depth

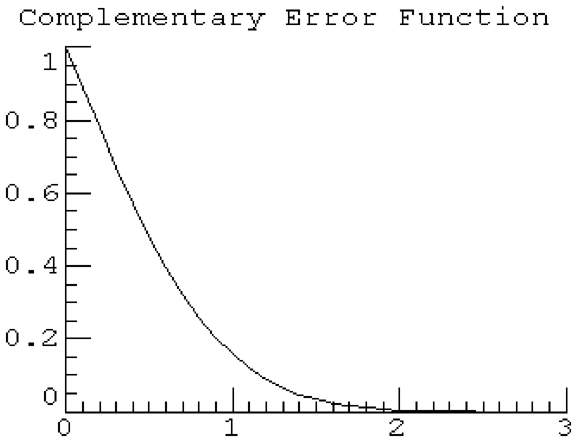
Solutions

- Error function (one-dimensional)

$$C_{(x,t)} = C_s\left\{1 - erf\frac{x}{2\sqrt{D\cdot t}}\right\}$$

(e.g. *fib* 34)

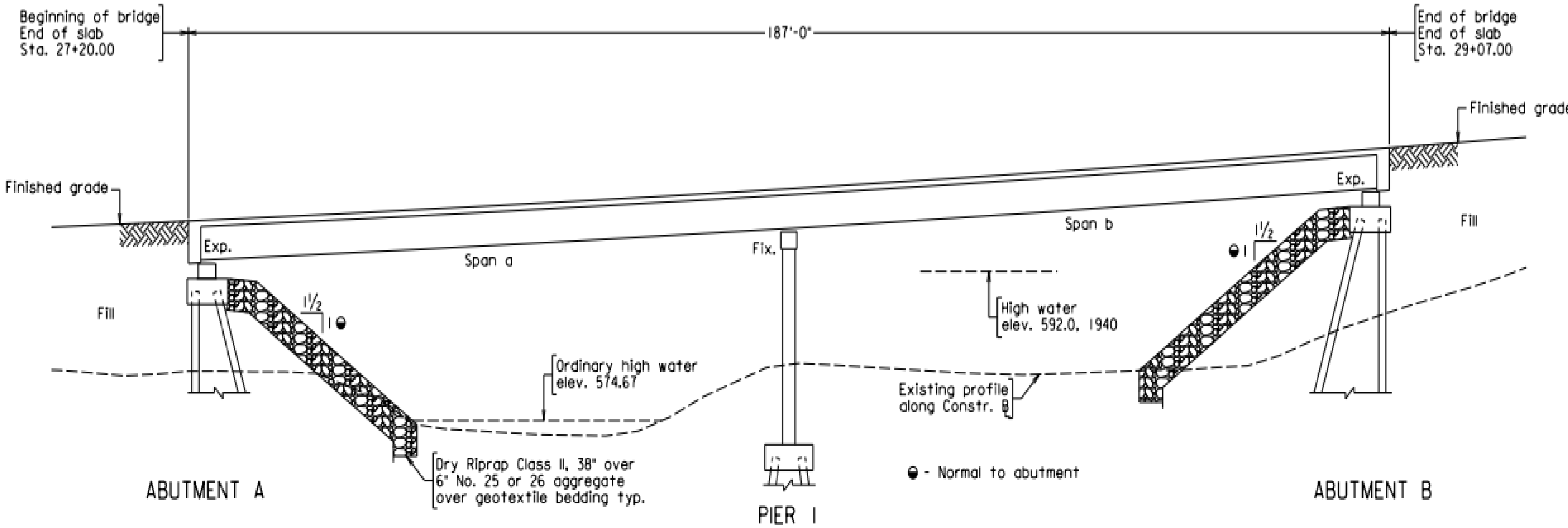
- Finite element



Complementary Error Function (1-erf)

Virginia Case Study

Model Corrosion Service Life of a Typical Virginia Highway Bridge Deck



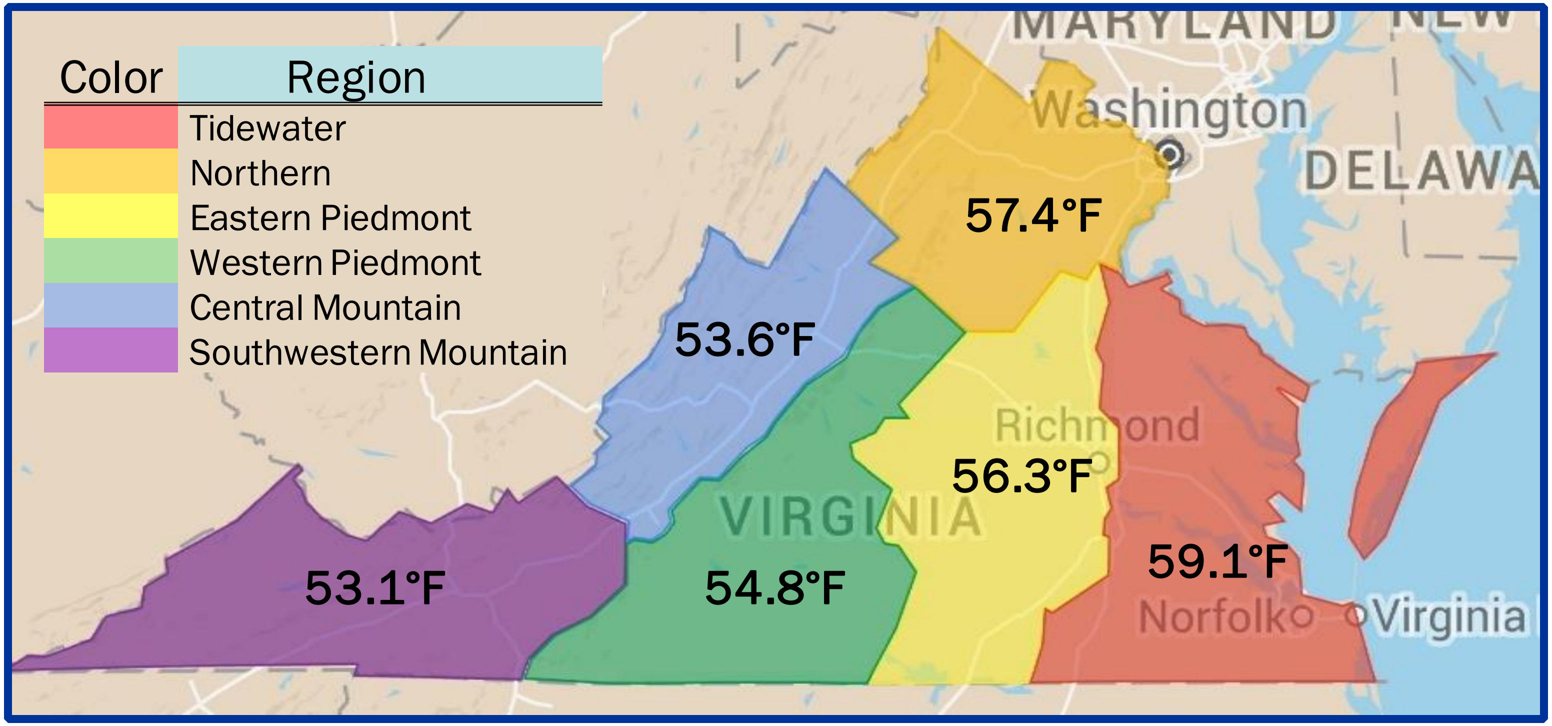
Service Environment

- Air Temperature
- Surface Chloride Concentration, C_s

Concrete Mix Properties

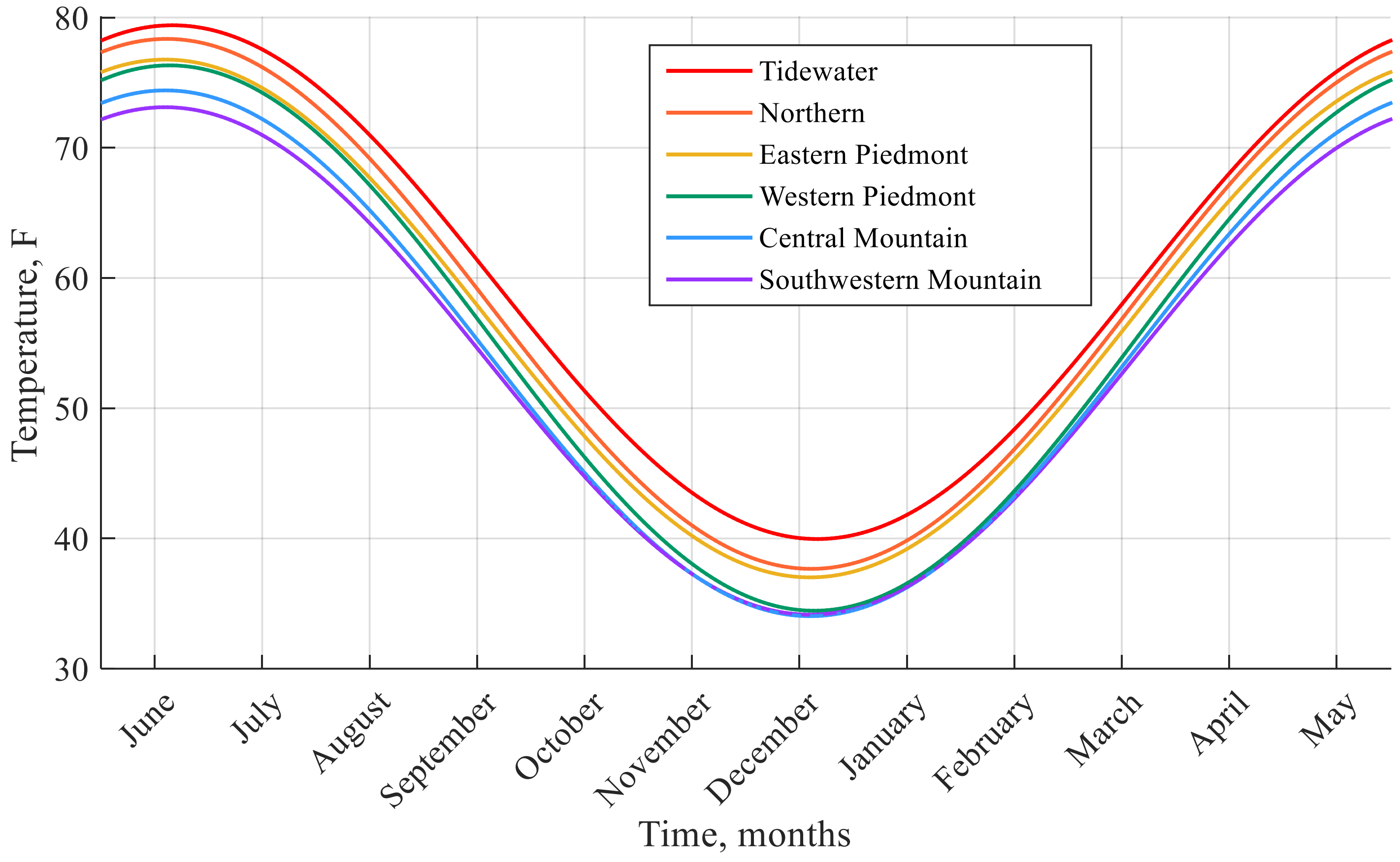
- Concrete Initial Chloride Concentration, $C_{(x,t=0)}$
- Chloride Migration Coefficient, D

Temperature Characterization



Yearly Temperature Regression

Typical Annual Temperature Cycles Developed from 30-years of Data

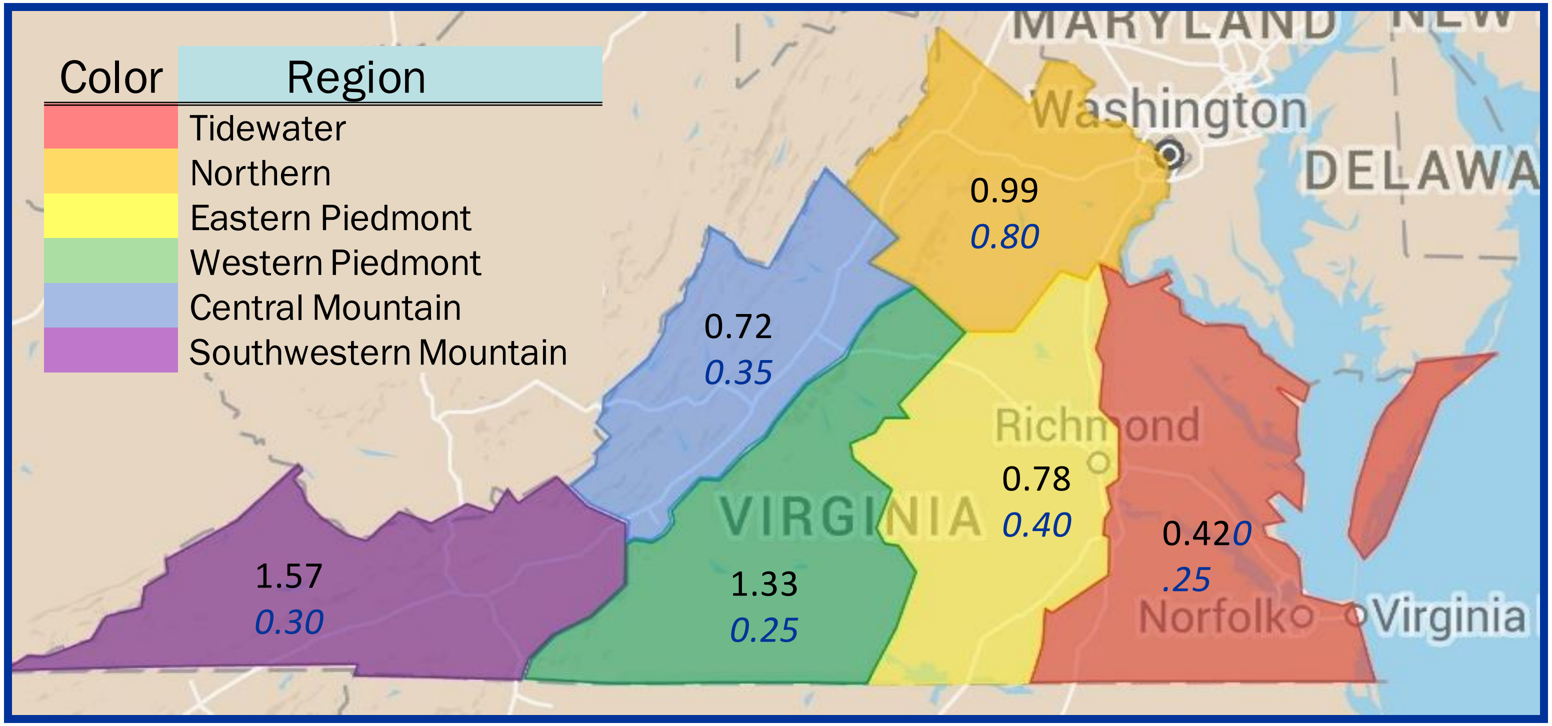


fib 34 Surface Chloride Concentration

Region	n, deicing events per year	$C_{s,i}$, average amount of Cl^- spread per year (Williamson 2007), $\frac{g}{m^2}$	$h_{s,i}$, amount of water from rain and snow during events, mm	C_{oR}, ave. Cl^- concentration of contaminated water due to deicing salts, $\frac{g}{l}$
Tidewater	12	38.2	221.0	0.173
Eastern Piedmont	11	90.0	132.7	0.686
Western Piedmont	12	37.4	237.7	0.157
Northern	29	742.2	223.4	3.323
Central Mountain	37	114.0	253.3	0.450
Southwest Mountain	42	116.9	284.7	0.304

Deicing event occurs if Snowfall > 0” and 20˚F < Temp < 32˚F

Surface Chloride Concentration



$$(\% \frac{mass\ Cl^-}{mass\ binder})$$

– Historical data (Williamson, 2007)

– fib 34-predicted

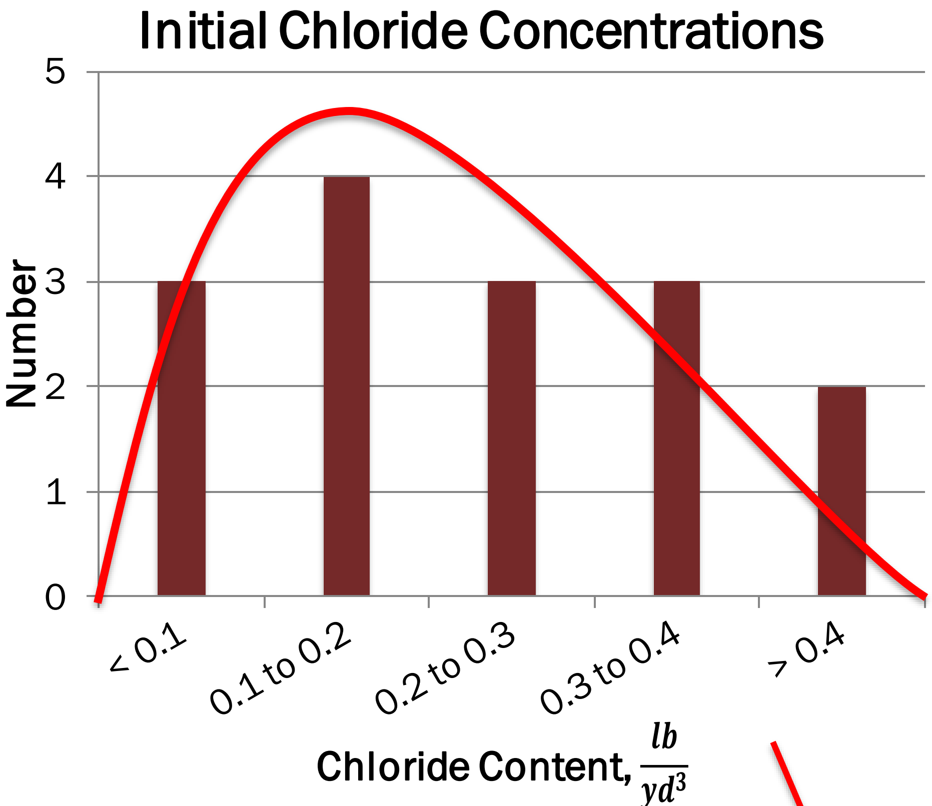
Virginia Concrete Mixes

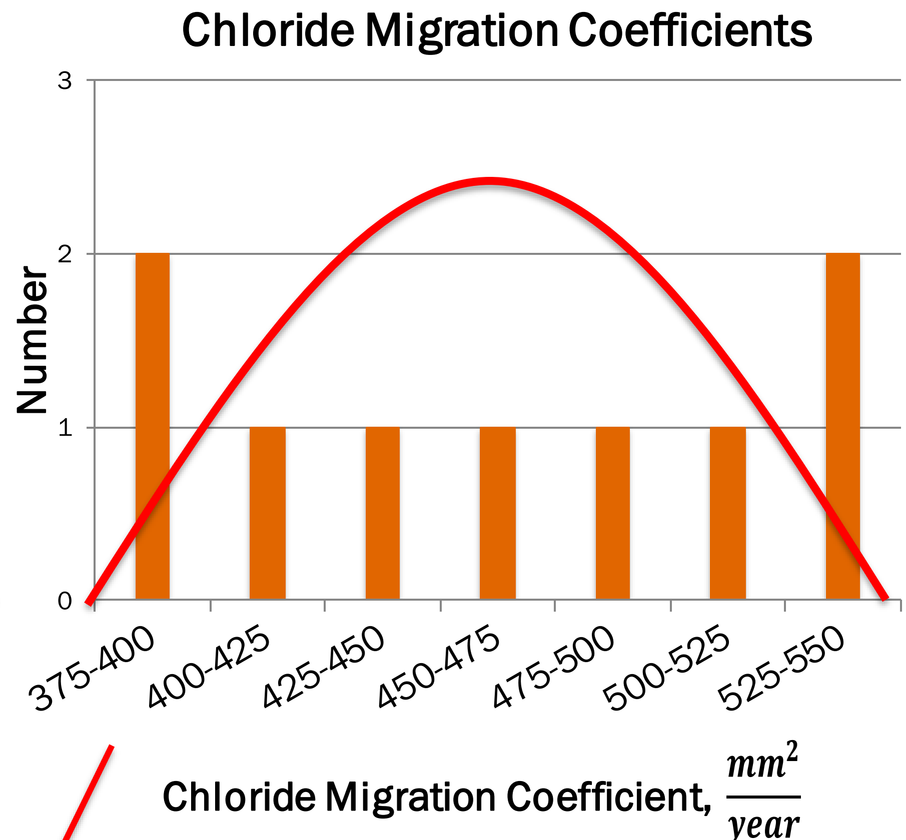
- Typical Deck mix (A4) – 4,000 psi HPC
  - All Virginia DOT concrete mixes contain mineral admixtures to reduce permeability
- Variety of source materials statewide
  - Limestone, diabase, etc.
- New low-cracking concrete specification
  - Limit on cementitious content (< 600 pcy)
  - Use of SRAs
  - Use of lightweight aggregates (CA and FA)

Concrete Mix Source Projects

Bridge #	District	Route & Over	Deck
01	Richmond	Rte. 226 over NSRR	Oct '15
02	Richmond	Rte. 712 (Wallace Rd) over North Meherrin River	Dec' 15
03	Richmond	Rte. 1 over CSX Rail Road (Phase I Construction)	Dec' 15
04	Bristol	Rte. 91 over N&W Railway & Rte. 609 (FIN 18971)	Jan' 16
05	Bristol	Rte. 52 over Wolf Creek	Jan' 16
06	Hampton Roads	*TBD*	
07	Hampton Roads	*TBD*	
08	Richmond	Rte. 1 over CSX Rail Road (Phase II Construction)	May '16
09	Staunton	Rte. 11 over North River	Fall' 16
10	Salem	*TBD*	
11	Salem	*TBD*	
12	NOVA	*TBD*	
13	Culpeper	*TBD*	
14	Fredericksburg	*TBD*	
15	Richmond	Rte. 360 over I-64, Exit 192	Jan '16
16	Richmond	Rte. 5 over Herring Creek	Jan '16
17	Lynchburg	Rte. 676 over Whitethorn Creek	Nov '15

Concrete Mix Properties





ASTM C 1152

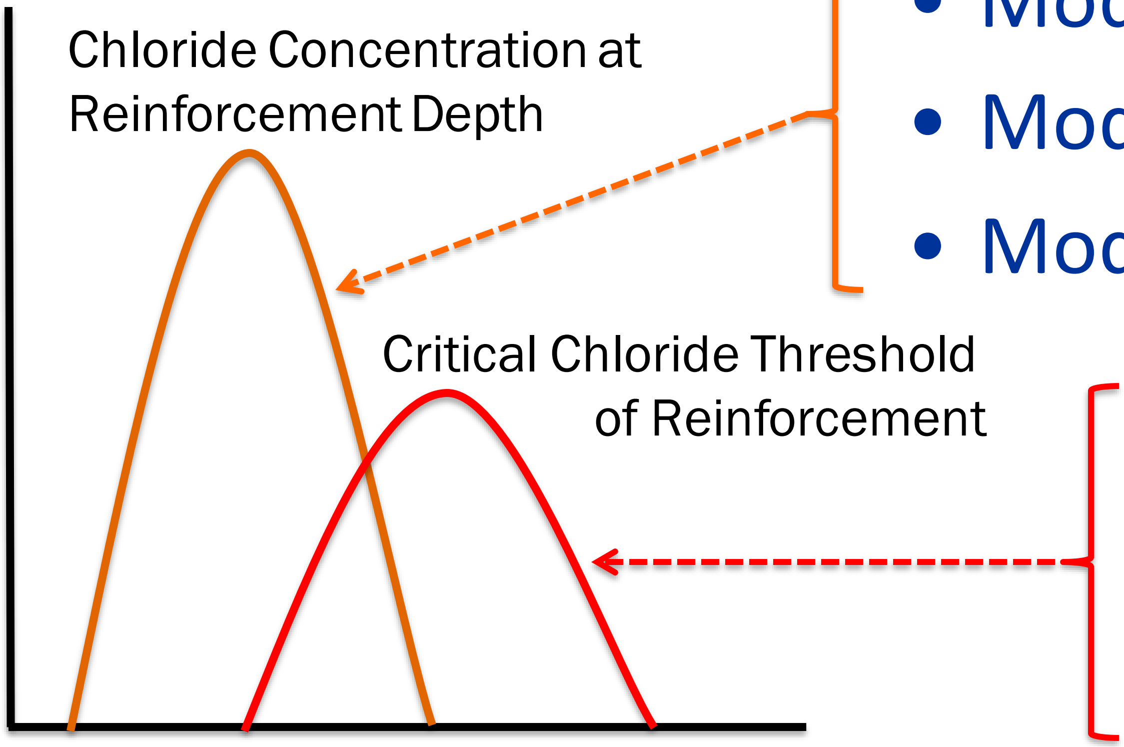
NT Build 492

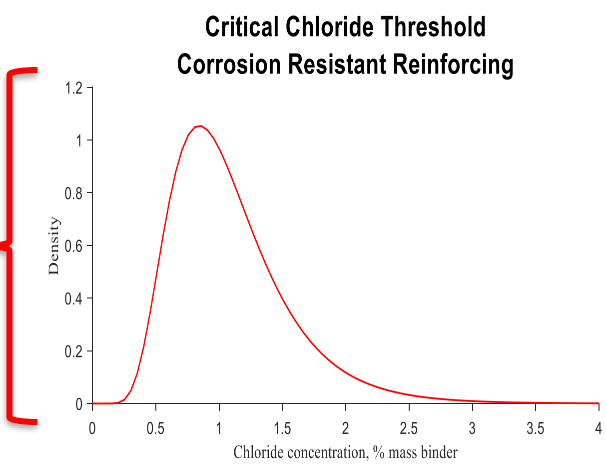
Model Input

Service Life Model Comparison

Predicting Probability of Corrosion Initiation

- Model *fib* 34
- Model *fib*-FEM
- Model TTMC-FEM





Model *fib 34*

$$C(x=a,t) = C_0 + \left(C_{s,\Delta x} - C_0\right)\left[1 - erf\,\frac{a-\Delta x}{2\sqrt{D_{app,C}\,t}}\right]$$

where

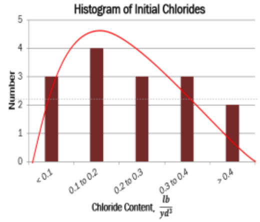
C_0 = initial chloride concentration

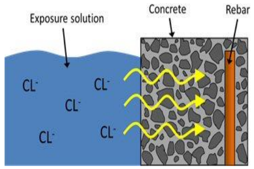
$C_{s,\Delta x}$ = surface chloride concentration

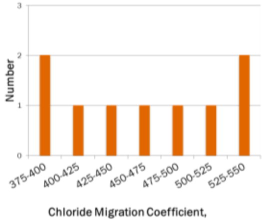
a = depth to reinforcing steel

Δx = depth of convection zone

$D_{app,C}$ = apparent diffusion coefficient







Apparent Diffusion Maturation

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

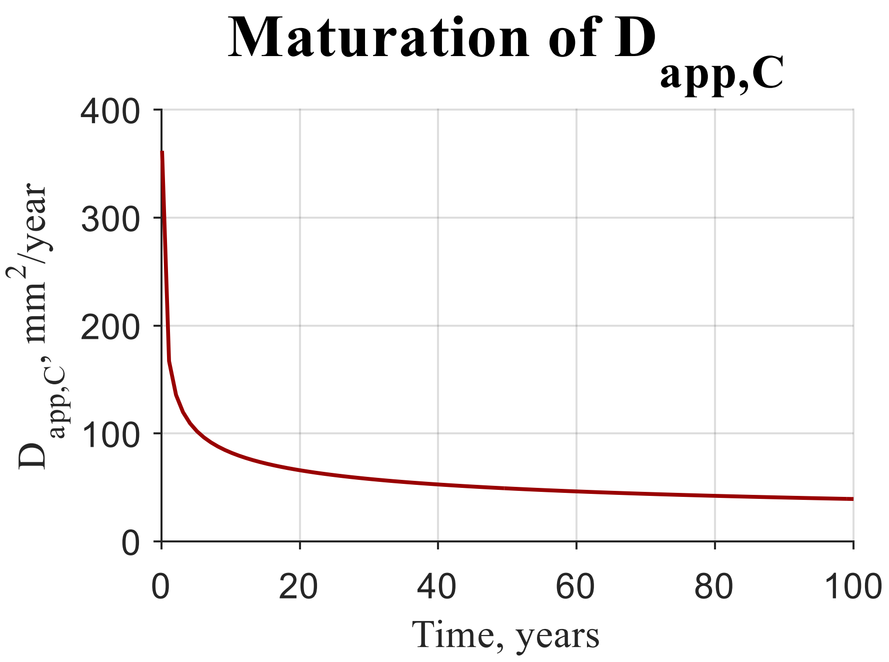
where

k_e= temperature adjustment

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

k_t= transfer parameter to account for accelerated carbonation test (usually k_t=1)

$A(t)$= aging subfunction



Model *fib*-FEM

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial a}\left\{D_{app,C}\frac{\partial C}{\partial a}\right\}$$

Finite Element Model Solution

where

- C = chloride concentration
- t = time of exposure
- a = depth
- $D_{app,C}$ = apparent diffusion coefficient, *fib* definition

Model TTMC-FEM

Time, **T**emperature, **M**oisture, **C**oncentration

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial a}\left\{D_{app}\frac{\partial C}{\partial a}\right\}$$

where:

C = chloride concentration

t = time of exposure

x = depth to reinforcing steel

D_{app} = apparent diffusion coefficient

$$D_{app} = D_0\, f_T\, f_\varphi\, f_{bind}\, f_{age}$$

where:

D_0 = chloride migration coefficient

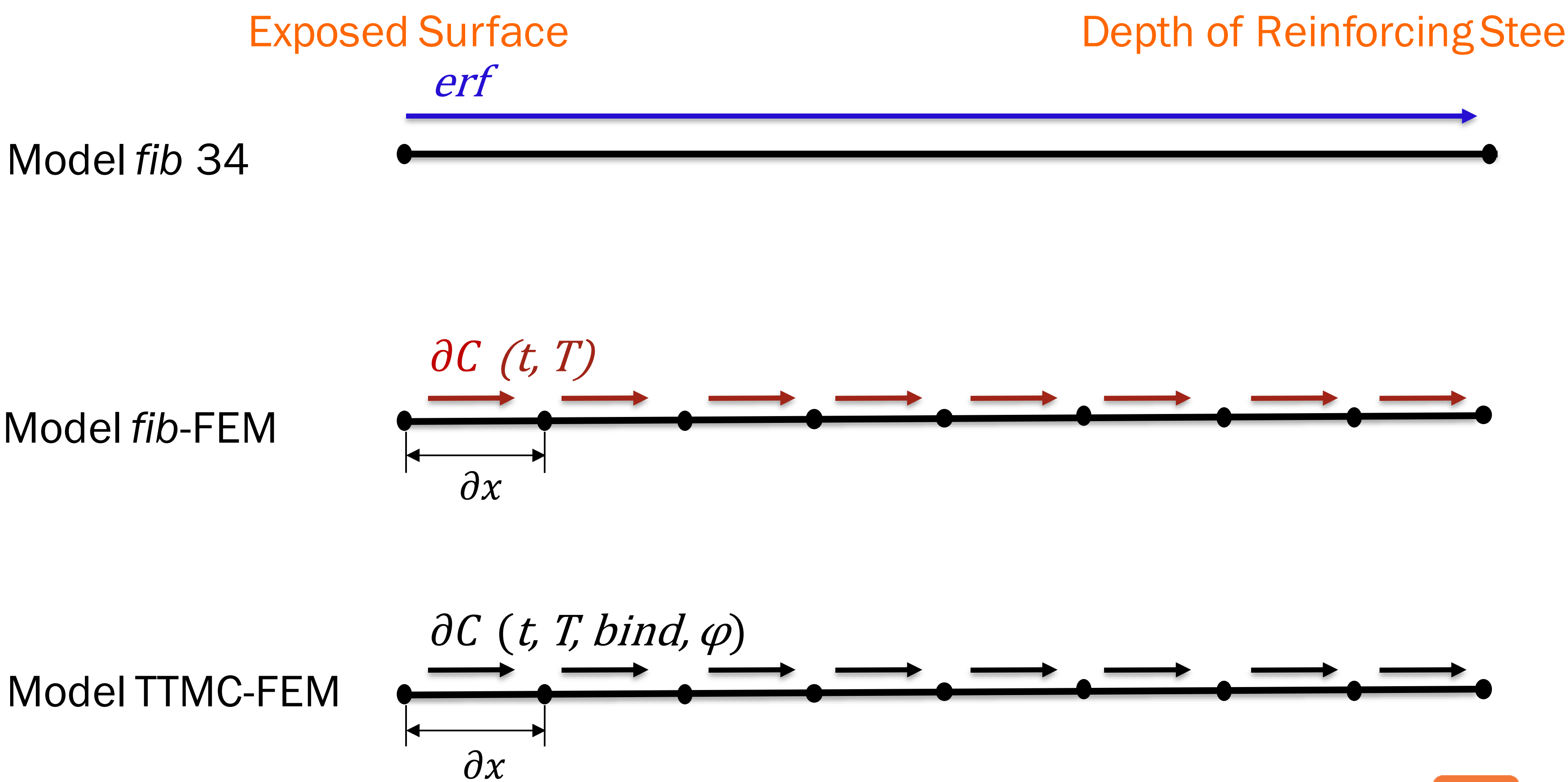
f_T = temperature adjustment

f_φ = moisture adjustment

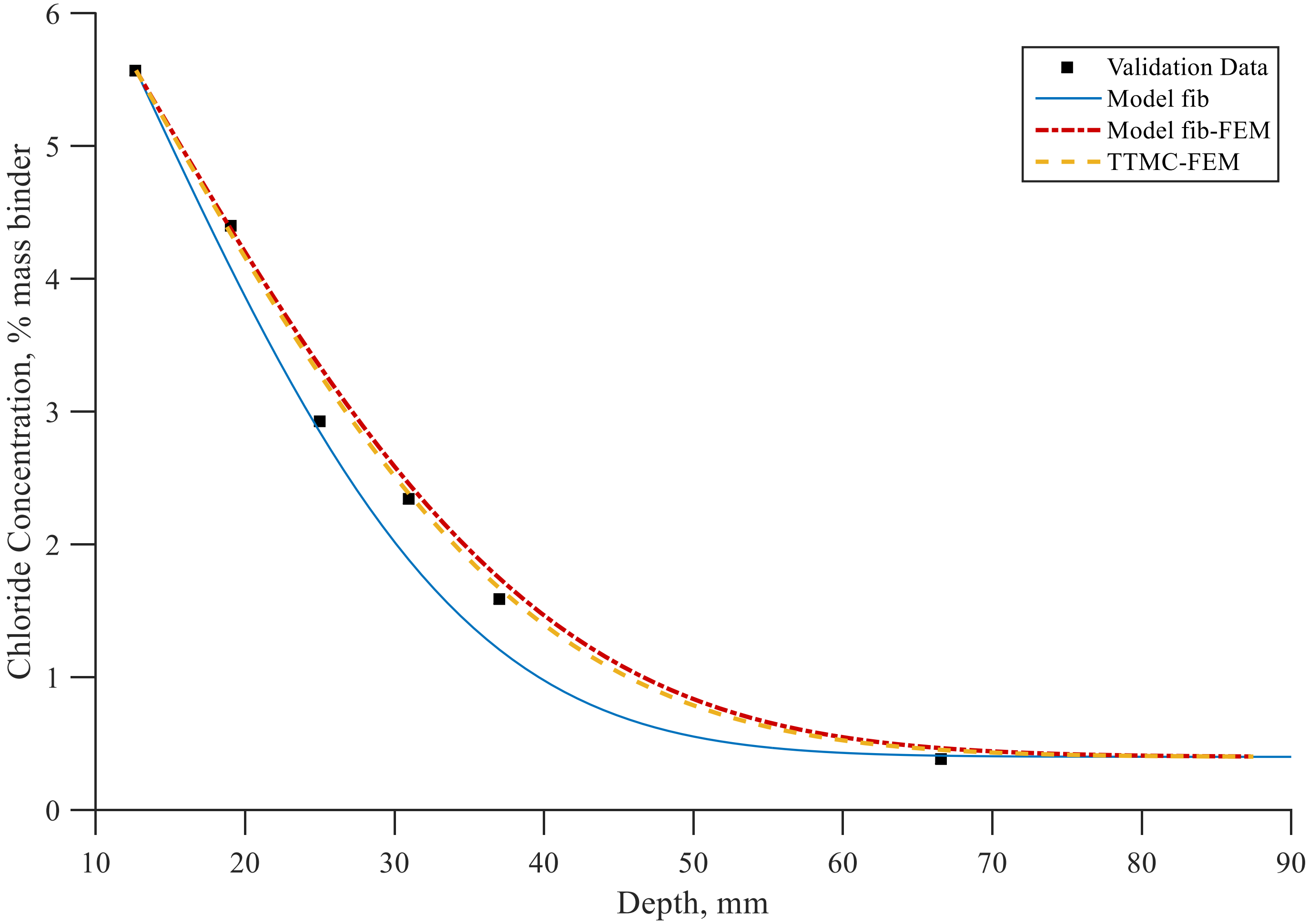
f_{bind} = binding adjustment

f_{age} = maturation adjustment

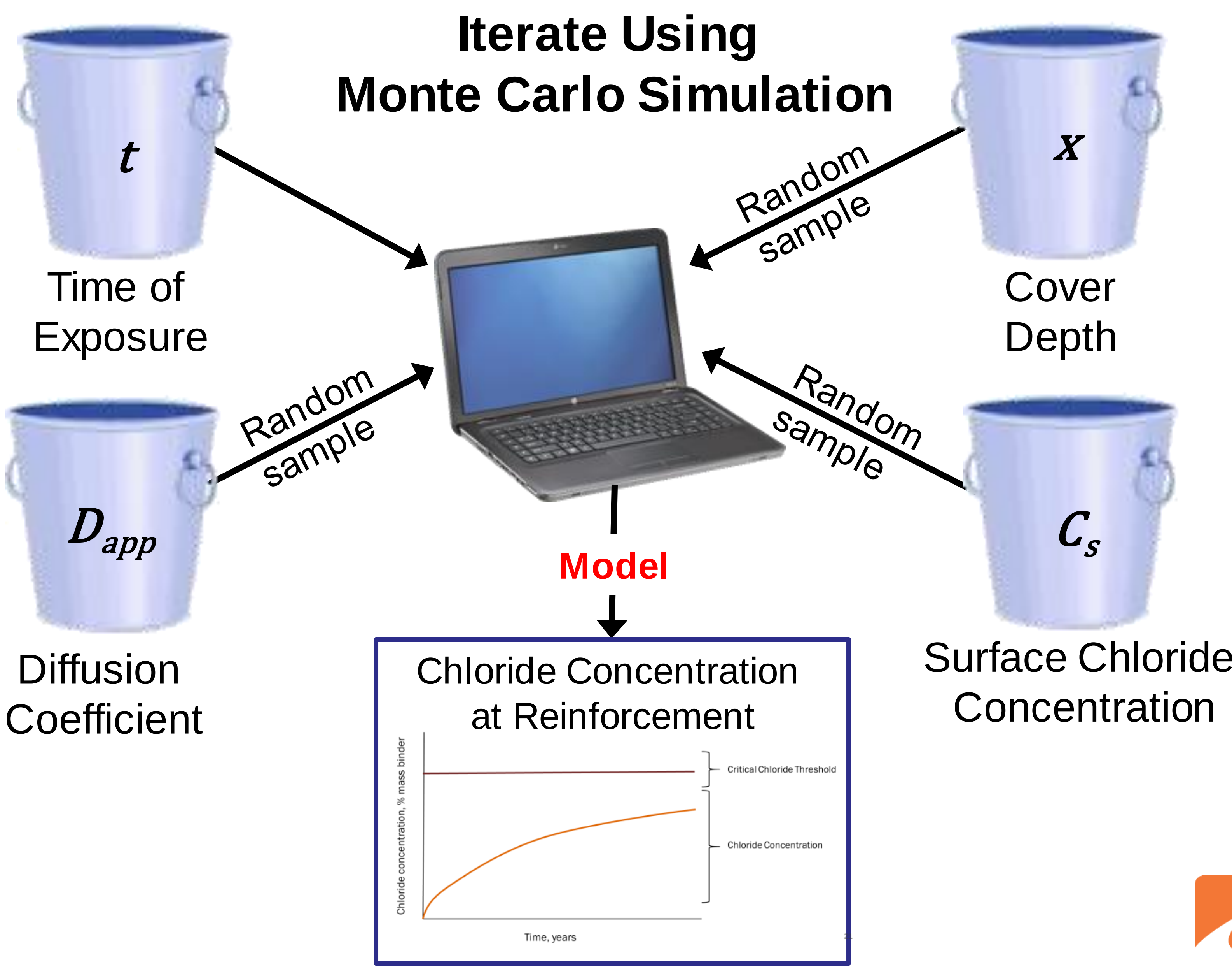
Model Comparison



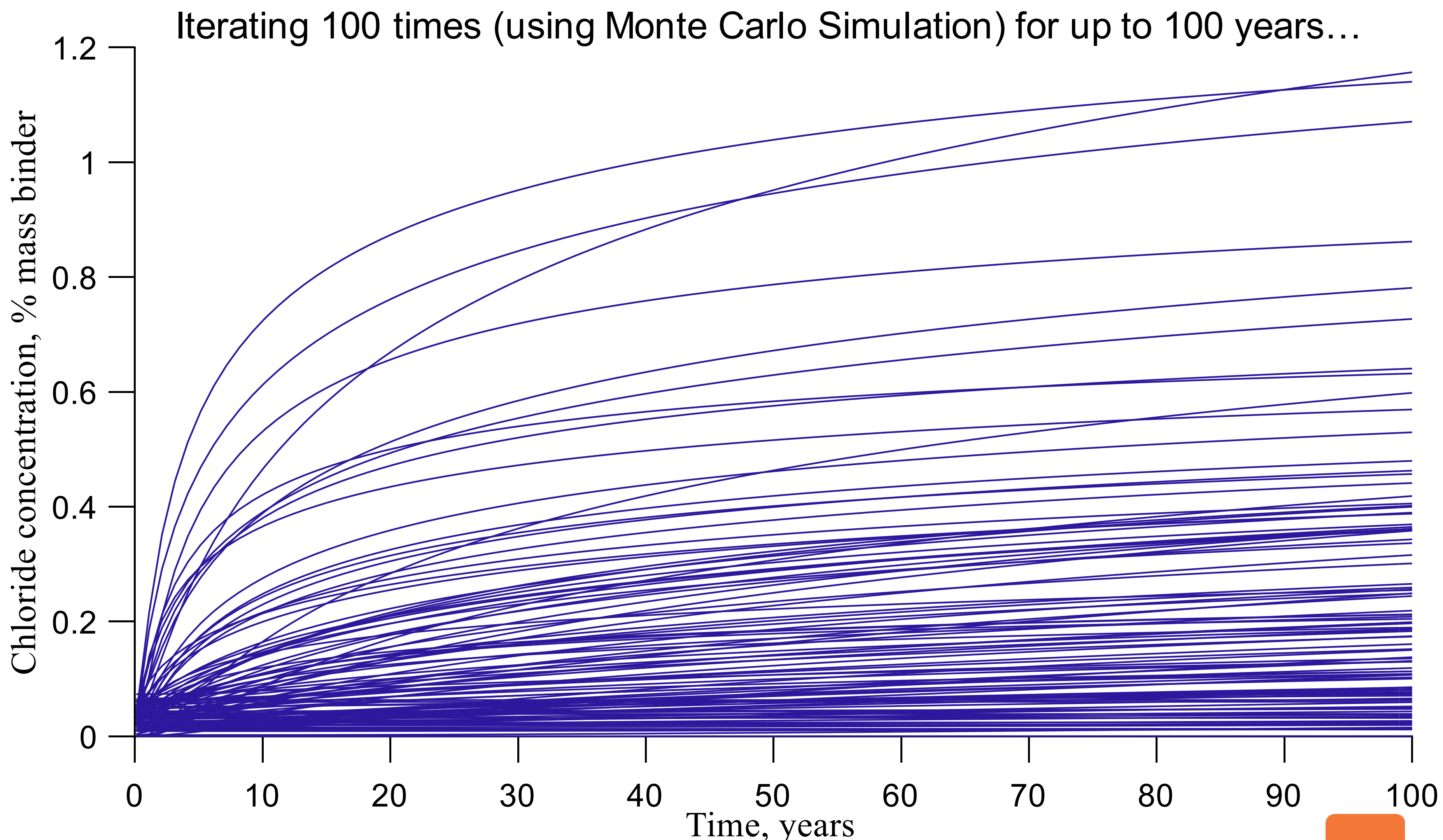
Example Model Fit



Model Processing



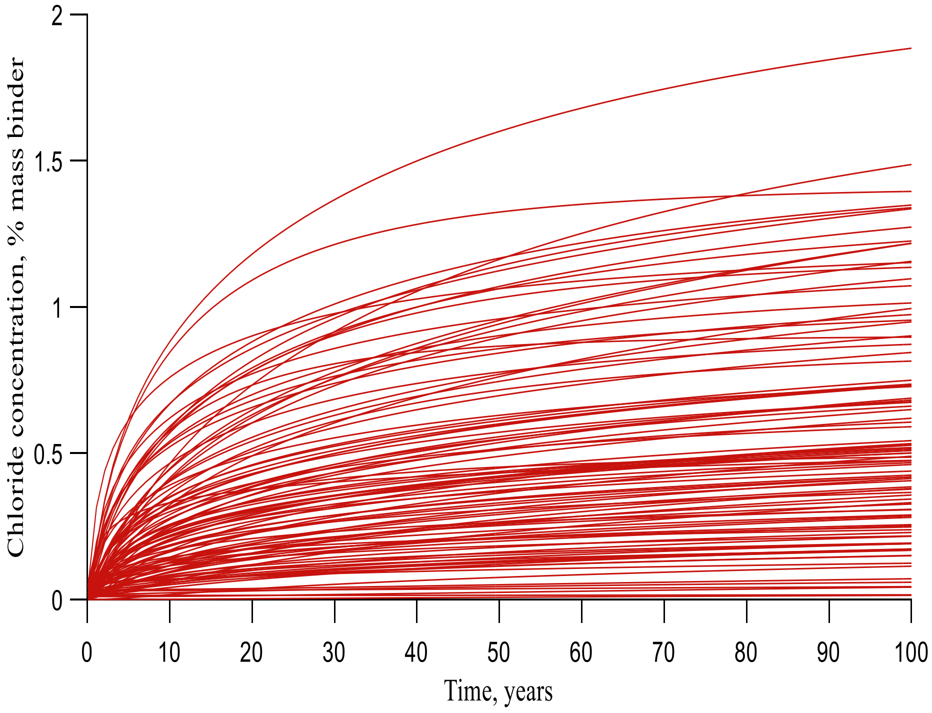
Model *fib 34* Cl^- Concentration



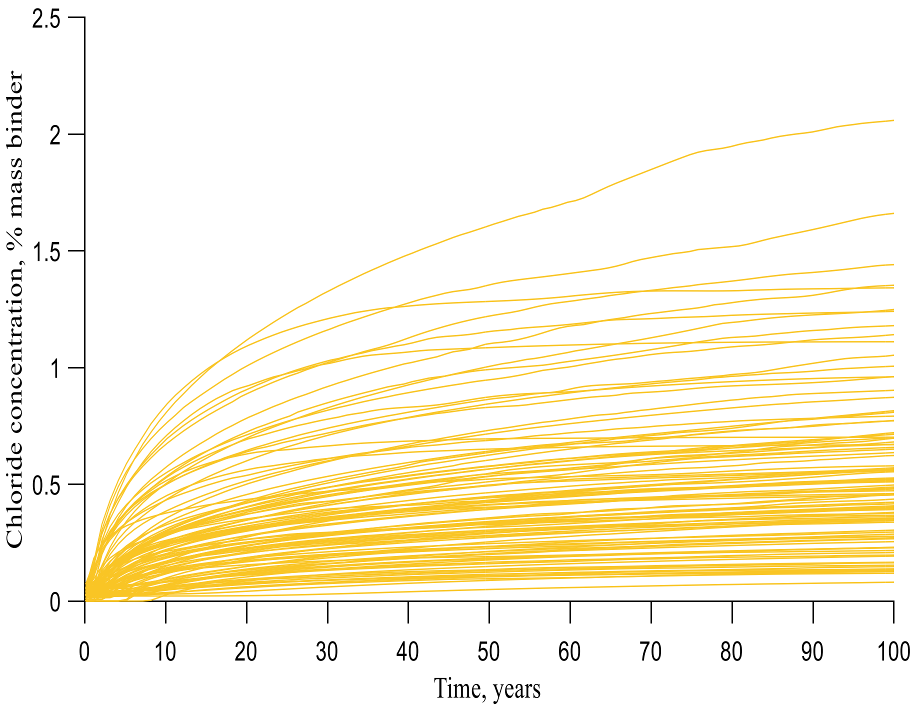
FEM-based Models

Similarly iterating for FEM-based models…

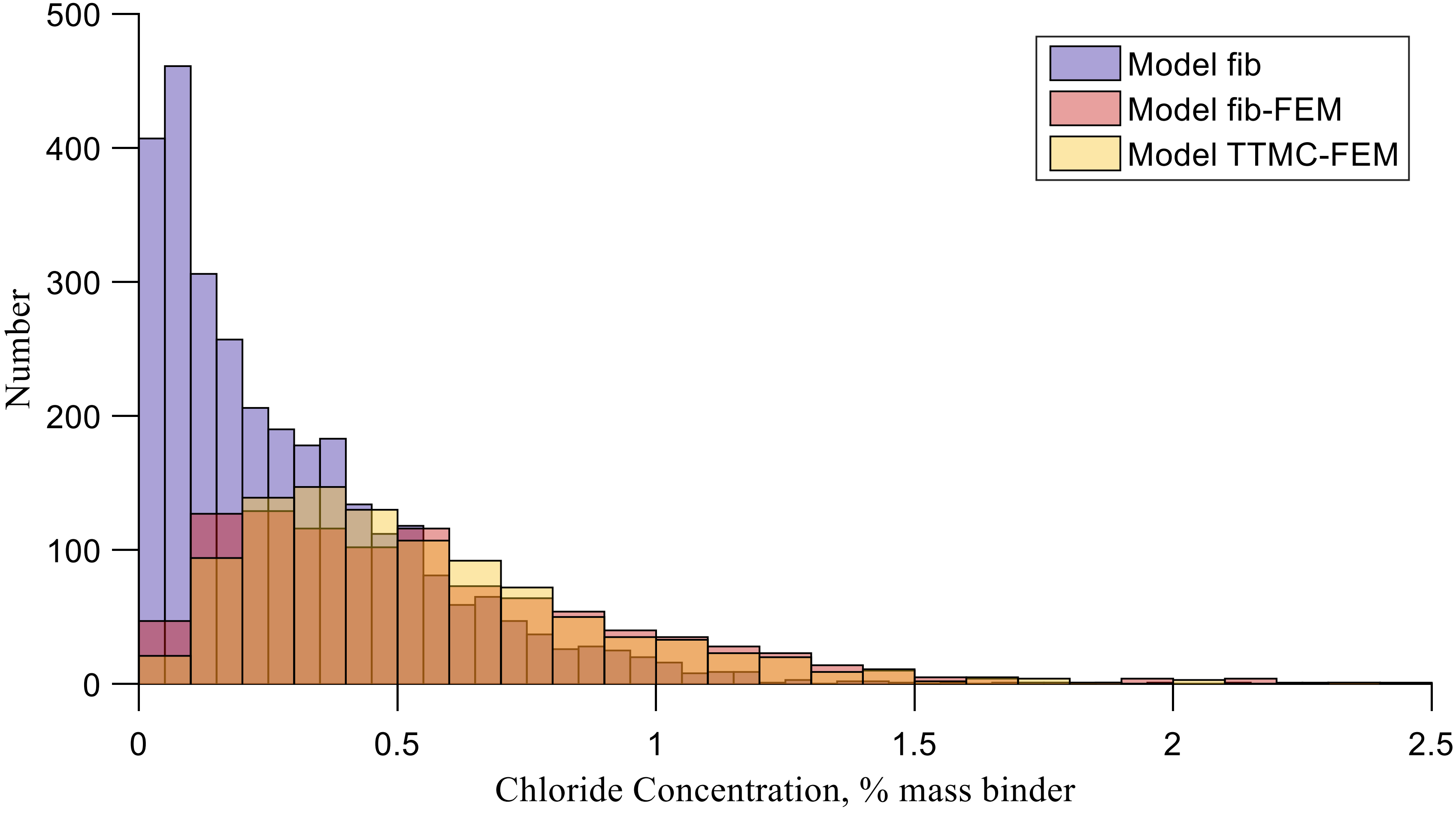
Model *fib*-FEM



Model TTMC-FEM

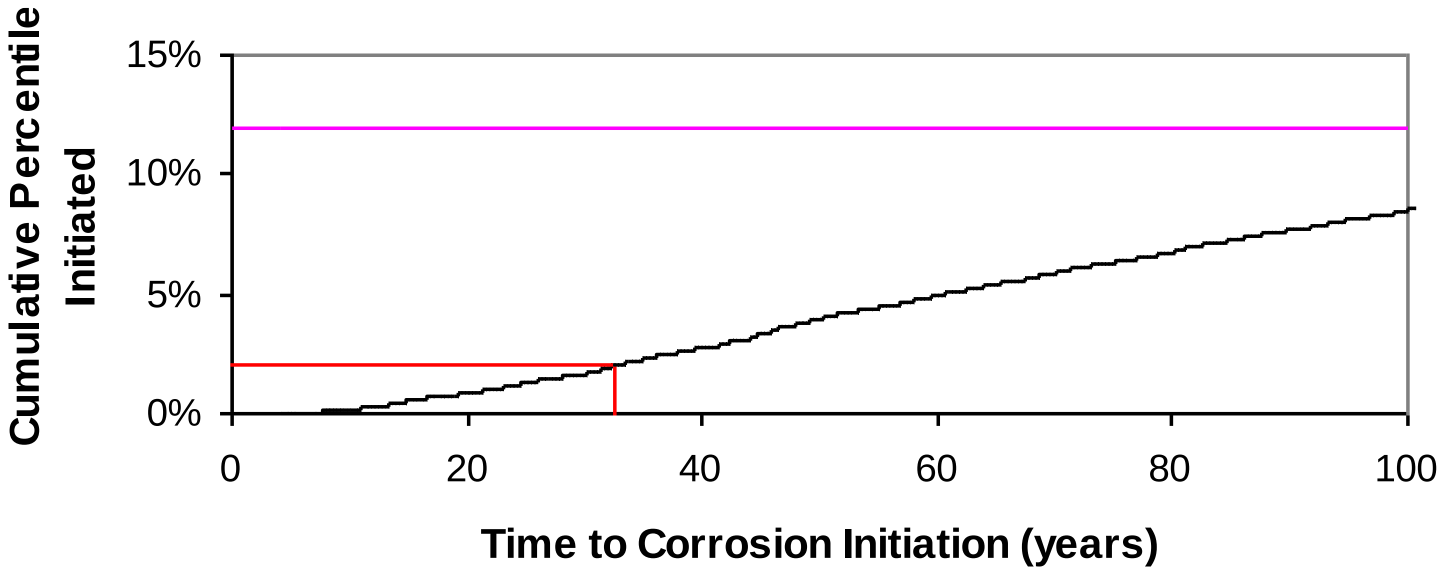


Model Comparison



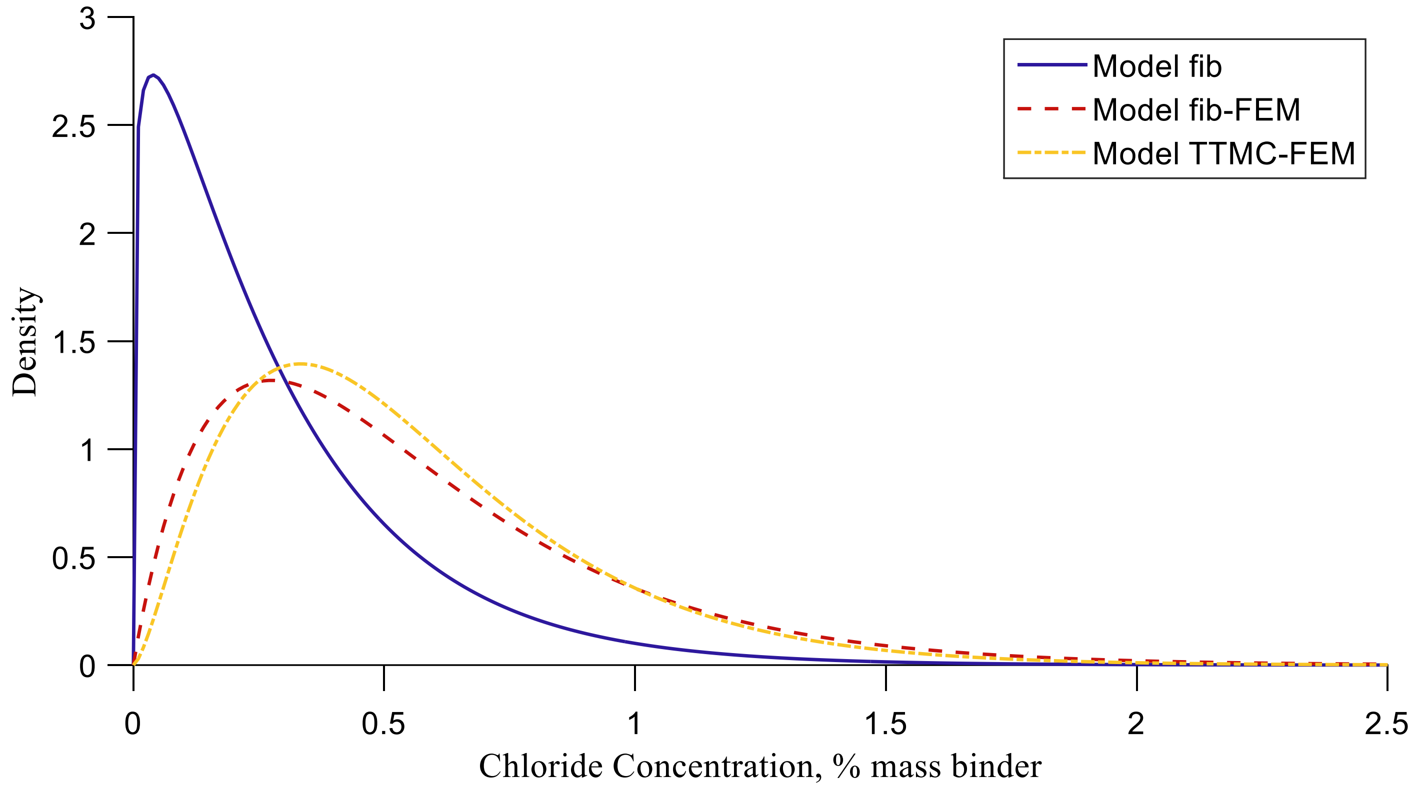
Probability of Corrosion

Employing a distribution of values for critical chloride concentration appropriate for the reinforcement…



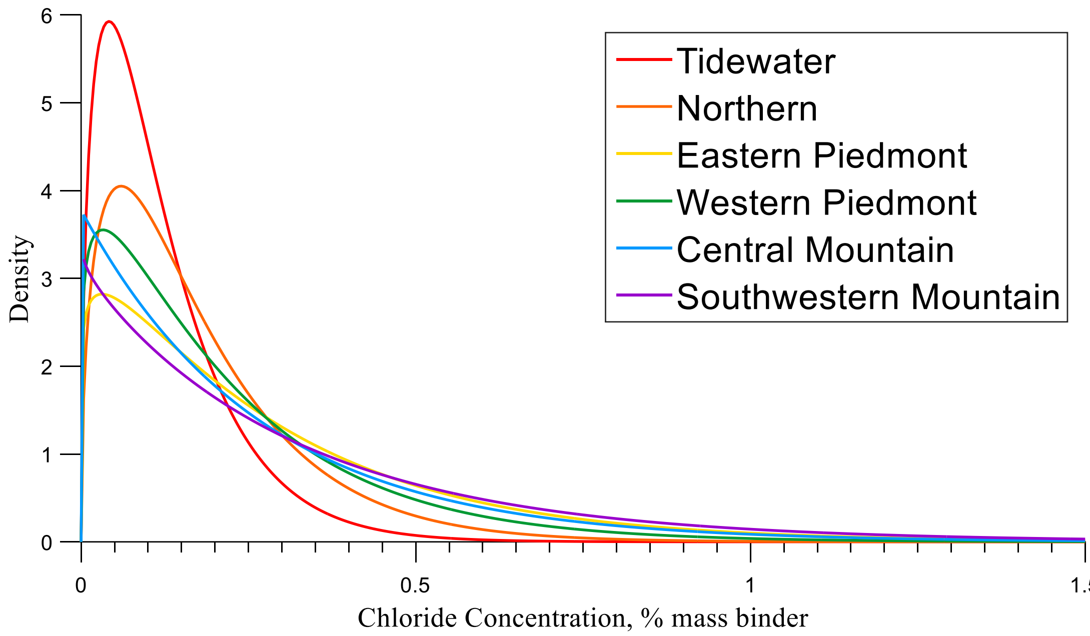
…one can determine probability that corrosion occurs within a set time.

Model Comparison



Model	Estimated Probability of Corrosion Initiation in 100 yrs
fib 34	4.70%
fib-FEM	16.2%
TTMC-FEM	16.5%

Model *fib 34* Regional Comparison



Region	Estimated Probability of Corrosion Initiation
Tidewater	0.36%
Northern	0.54%
Eastern Piedmont	4.70%
Western Piedmont	2.19%
Central Mountain	4.67%
Southwestern Mountain	7.11%

Conclusions

- Diffusion models based on *fib 34* or FEM can be used to project service life of bridge decks
- Some models may be more sensitive to in-service parameters, such as temperature, moisture and maturity

Continuing work:

- Additional concrete data from new decks
- Update Virginia chloride usage data
- Adapt models for comparison of design options (reinforcement type, concrete, coatings, etc.)

Acknowledgments

- Elizabeth Bales

  Graduate Research Associate, Virginia Tech
- Madeleine Flint

  Assistant Professor, Virginia Tech
- Prasad Nallapaneni

  Assistant State Structure and Bridge Engineer, VDOT

Thank You

Contact information:

Michael.Brown@VDOT.Virginia.gov