Durability Modelling of Concrete Elements in Tunnel and Underground Environment

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Career Highlight

1. 1985-1988, Assist Engineer, Heilongjiang Academy of Cold Region Construction (China)
2. 1988-1990, M.Eng. Student, Tsinghua University (China)
3. 1990-1996, Lecturer, Beijing University of Technology (China)
4. 1996-2001, Ph.D. Student/Research Fellow, University of Dundee (China)
5. 2000.5-11, Research Fellow, National Unvisited of Singapore
6. 2002-2007, R&D Manager, Boral Concrete (Australia)
7. 2007-2012, Principal Materials Engineer, AECOM (Australia)
8. 2013-2017, Principal Materials Consultant, ANCON Beton P/L (Australia)
9. 2017-2020, Principal Engineer-Civil/Materials of BCRC(Q) P/L (Australia)
10. 2020-Now, Director, National Engineering Manage, Bell Asset Engineering P/L (Australia)

    [2023-Now, National Director - Materials Engineering (Adjunct), Renovo Solutions P/L, Australia]

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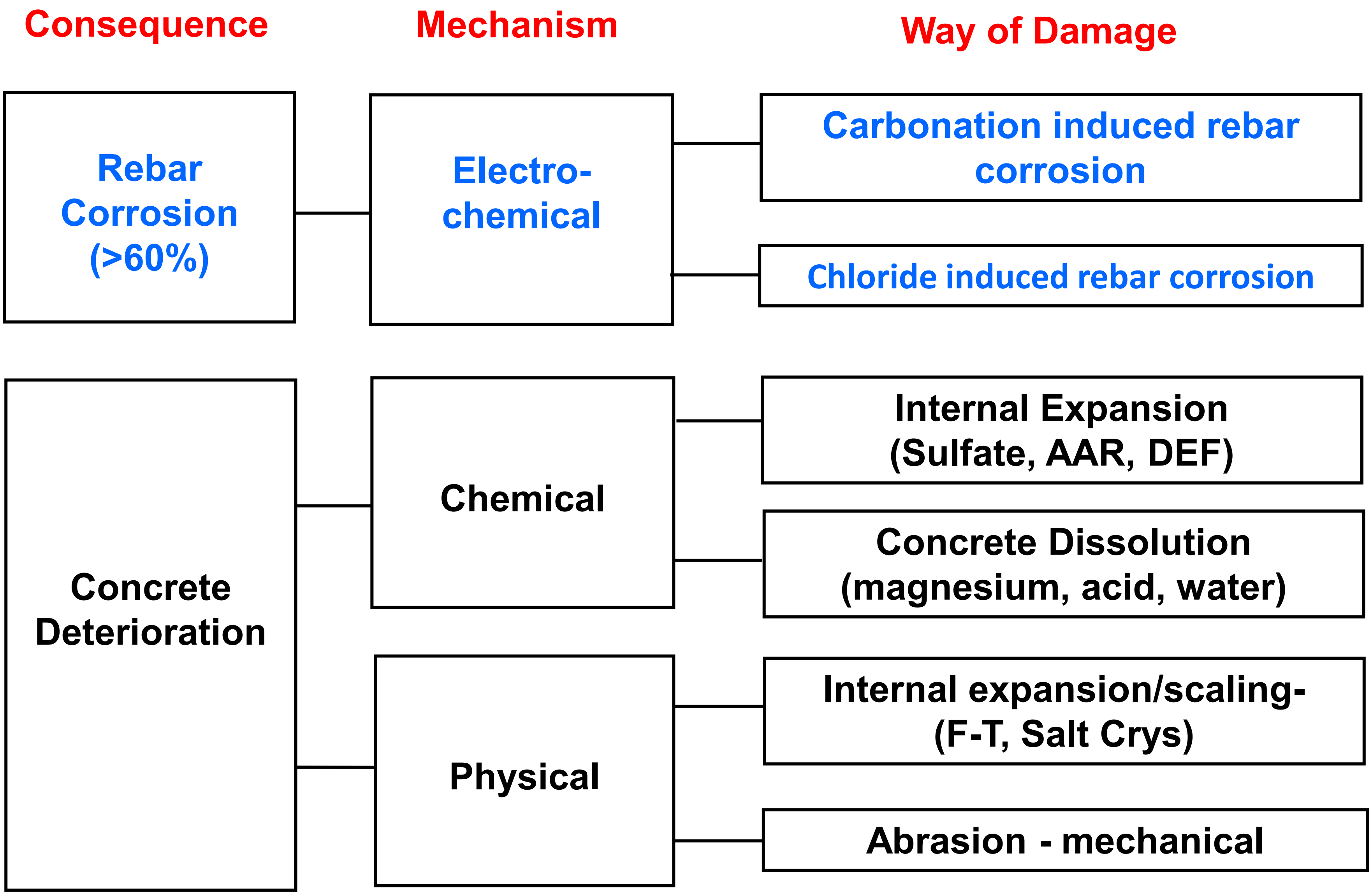
3. Carbonation models and application in tunnel elements
4. Rebar corrosion modelling in tunnel elements

1, Deterioration by Rebar Corrosion & General Model

Concrete Deterioration Mechanisms

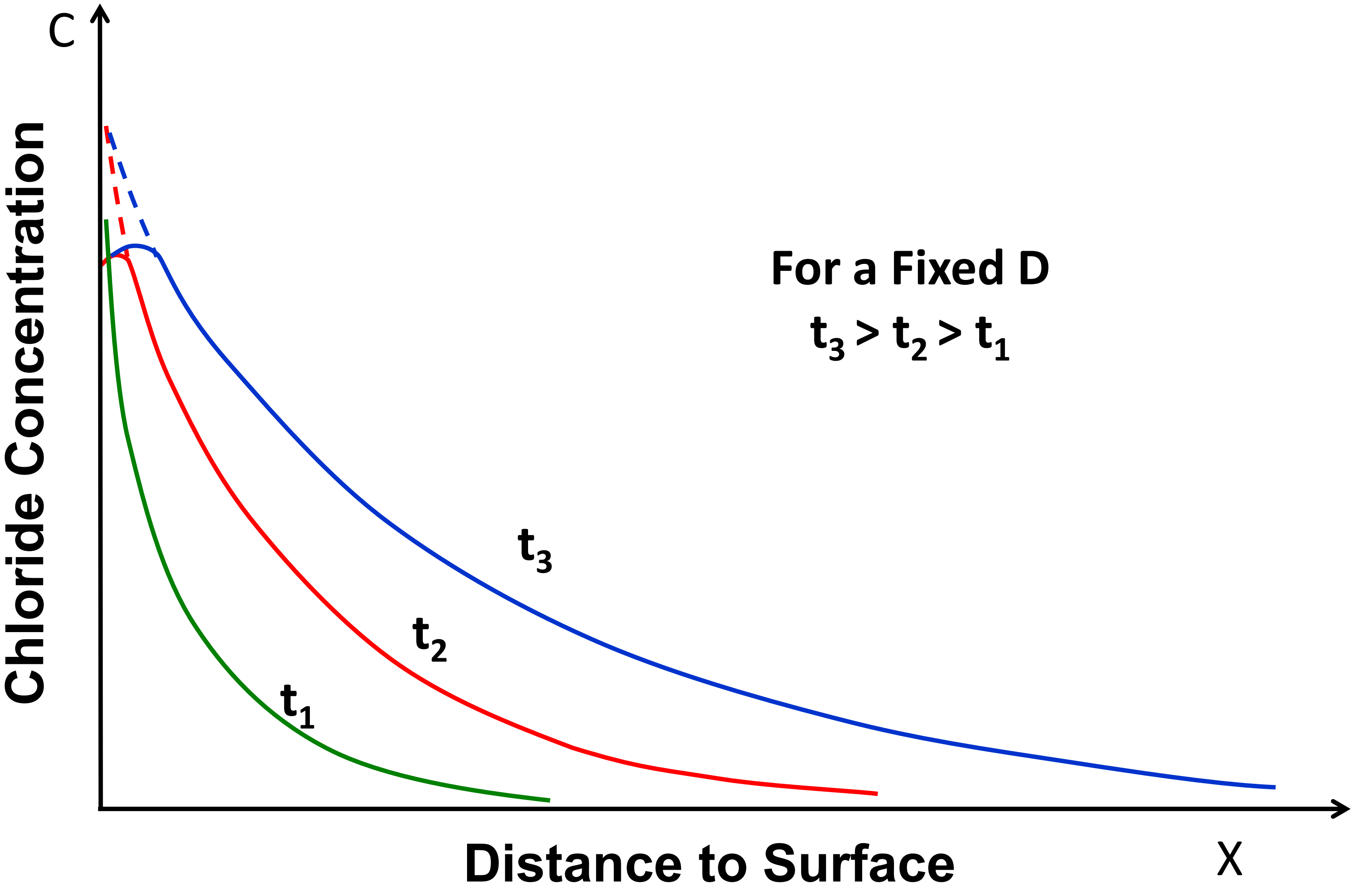


fib Bulletin 59, Condition Control and Assessment of Reinforced Concrete Structures, Lausanne, Switzerland, 2006

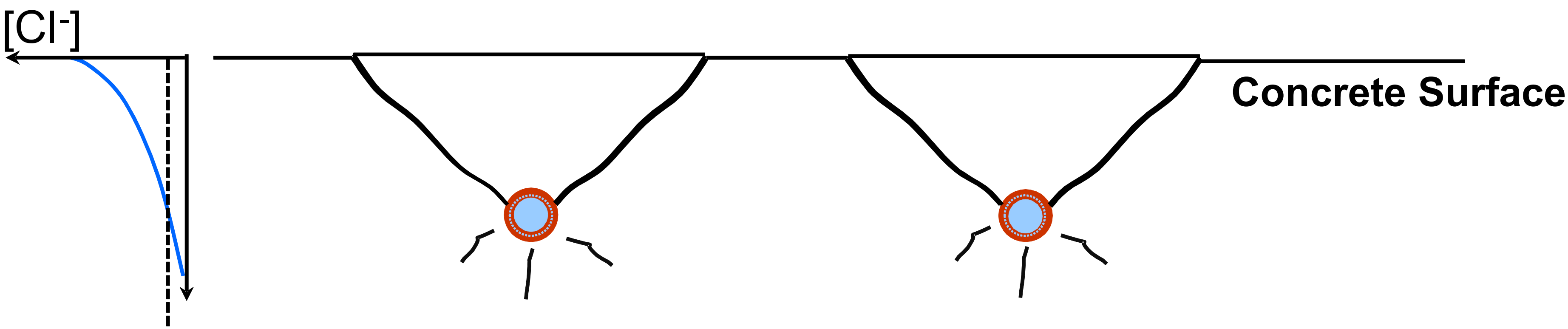
Chloride Ingress and Consequences

- Chloride ions transport into concrete via **Diffusion, Absorption, Permeation & Wicking**
- Pore in concrete **>1 µm** vs chloride Ion is **0.2 nm**: like through **3 mm** rice grain vs **15 m** dia tunnel
- Chloride ion concentration increases to **threshold** level of **0.06%** for carbon steel
- Original **passive layer** on steel bar surface destroyed
- **Corrosion** of rebar starts
- **Rust** has a higher volume (2-6 times) than original steel
- **Expansive force** destroys concrete cover

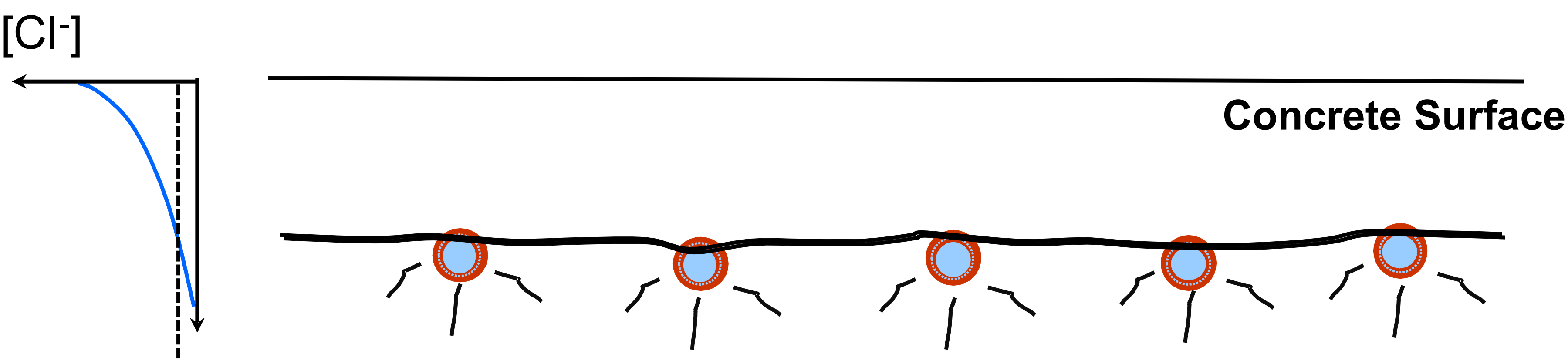
Chloride Diffusion in Concrete – Semi Infinite



Chloride Induced Reinforcement Corrosion and Concrete Deterioration



(1) Chloride induced corrosion of reinforcement and spalling of cover concrete



(2) Chloride ions induced corrosion of reinforcement and delaminating of cover concrete

Chloride-Induced Rebar Corrosion & Deterioration

Carbonation & Consequences

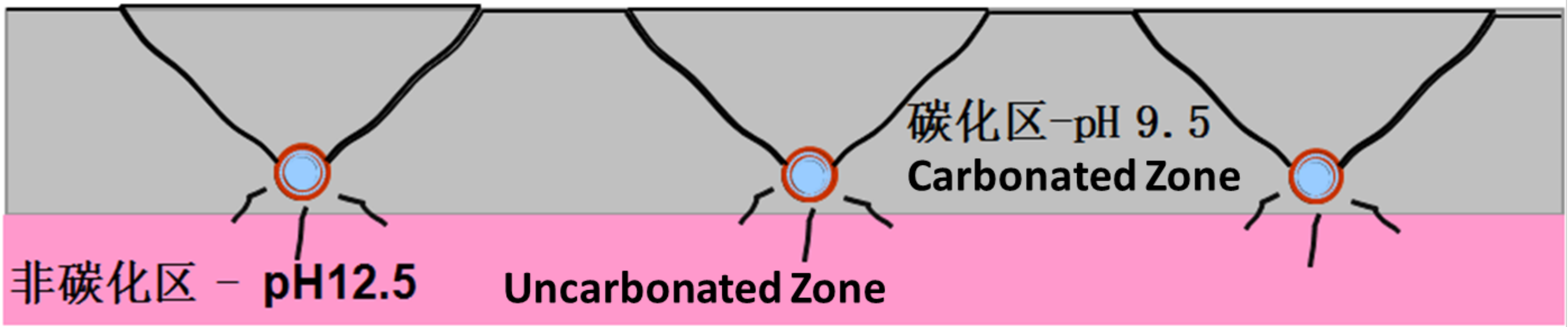
- **Carbonation Reactions**

  $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

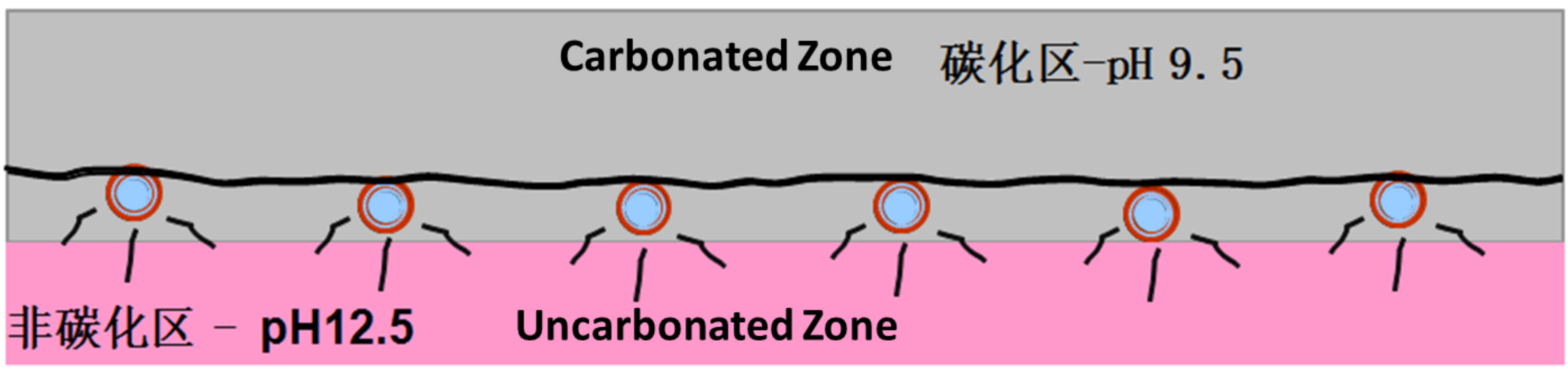
  $3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 3H_2O$

- **CO_2 enters** concrete via gaseous diffusion under concentration gradient
- **pH** decreases from 12.5 to 9.5
- Original **passive layer** on steel reinforcement surface destroyed
- **Corrosion** of rebar starts
- **Rust** has a higher volume (2-6 times) than original steel
- **Expansive force** destroys concrete cover

Carbonation Induced Reinforcement Corrosion and Concrete Deterioration



Spalling Caused by Reinforcement corrosion



Delaminating Caused by Reinforcement corrosion

Carbonation-Induced Rebar Corrosion & Deterioration

Durability Design Methods for Rebar Corrosion Deterioration

1) **Deemed to satisfy**: comply with current standards and codes

2) **Avoidance of deterioration**: use of non-corrosive materials such as non-reactive aggregate and stainless steel etc.

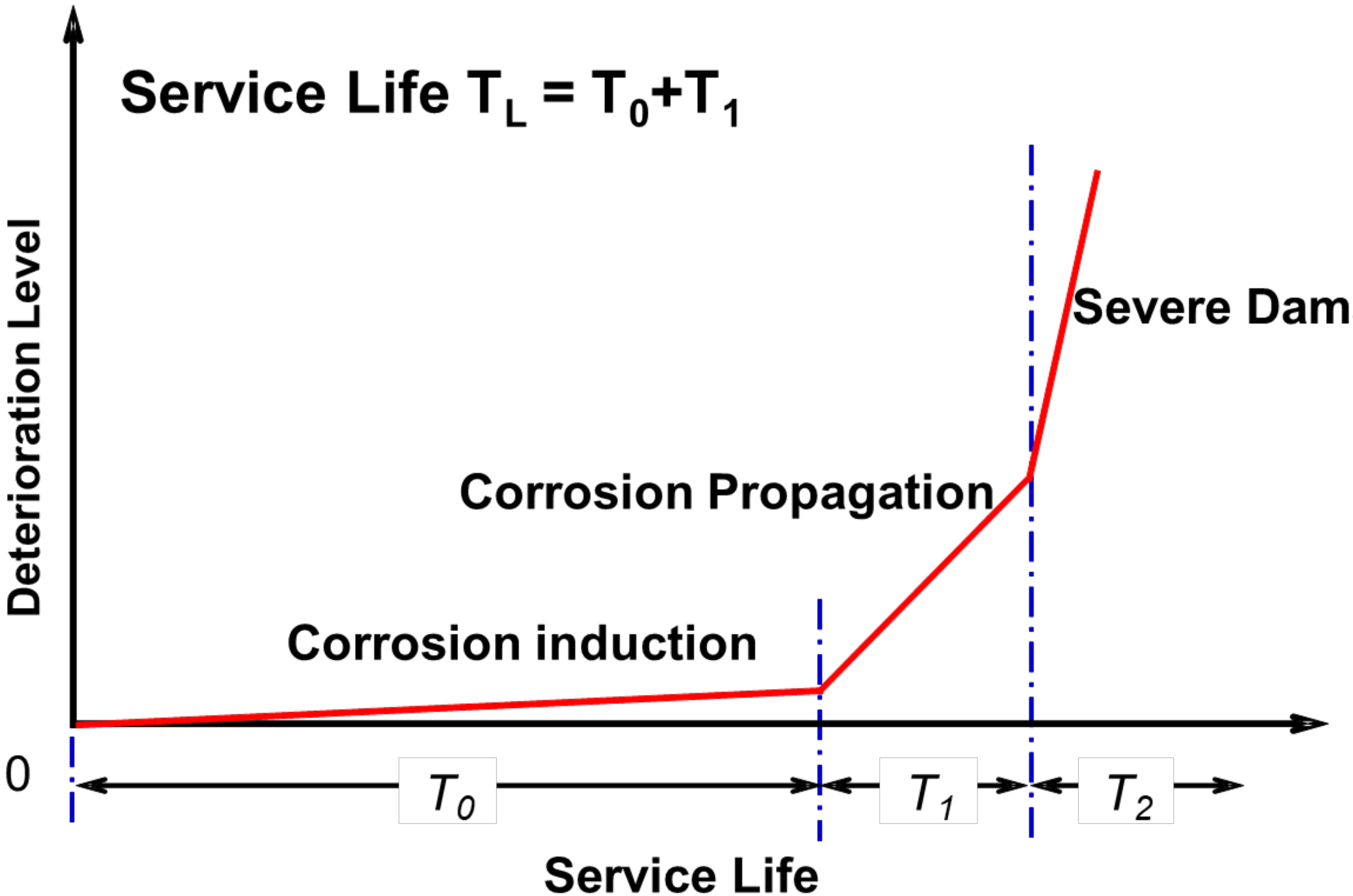
3) **Modeling - Full probabilistic**: mathematic modeling using variable inputs to estimate the probability of a service life

4) **Modeling - Partial factor**: mathematic modeling using average inputs to estimate the service life and add a safety margin to promote reliability

5) **Modeling – Partial probabilistic**: mathematic modelling with cover distribution and average values of other factors - **BAE Method**

Based on mainly : fib Bulletin 34, Model Code for Service Life Design, Lausanne, Switzerland, 2006

General Model of Rebar Corrosion & Deterioration



Tuutti, K., Corrosion of steel in concrete, Swedish Cement and Concrete Research Institute, Report No. 4-82, pp 469, Stockholm, Sweden,1982

Service Life Calculation

Service or design life of concrete structures normally can be calculated by summing corrosion initiation period and corrosion propagation period

$$T_L = T_0 + T_1$$

T_L Service or design life, yr
T_0 Corrosion induction period, yr
T_1 Corrosion propagation period, yr

Tunnels and Underground Environments

1. External Environments:

1.1 Soil & Groundwater may contain following deleterious agents:

chloride, acid, sulfate, magnesium,

1.2 Seawater contains:

chloride, sulfate, magnesium

Main Deterioration: chloride induced rebar corrosion, chemical attack by acid, sulfate & magnesium

2. Tunnel Internal Environment containing :

Normal level CO_2 in train tunnels

Elevated level of CO_2 in road tunnels

Main Deterioration: carbonation induced rebar corrosion

2, Chloride Models and Application in Tunnel Elements

Fick's First Law of Diffusion

Fick's First Law of Diffusion

$$J = -D \frac{\partial C}{\partial X}$$

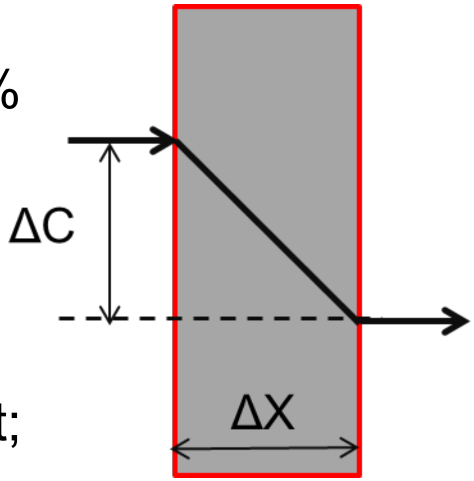
Where,

J: is the diffusion flux (or rate of mass transfer) through unit area in unit time

D: is Diffusivity, m^2/s or $mm^2/year$

C: is concentration of media, e.g. chloride ions etc., %

X: is the distance of locations, m or mm



Significance:

- Diffusion flux is proportional to concentration gradient;
- Relates the medium concentration to the location.

Fick's Second Law of Diffusion

Fick's Second Law of Diffusion

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial X^2}$$

Significances:

- Change of medium concentration has a linear relationship to the second derivative of concentration with location
- It relates the medium concentration change with time to the location**.**
- **Time** is related in this law.

First Generation (1G) Analytical Chloride Model – Solution to Fick's Second Law

First Generation Model **(**Collepardi,1972**)**

$$\frac{C - C_0}{C_s - C_0} = erfc\left(\frac{X - \Delta X}{2\sqrt{Dt}}\right)$$

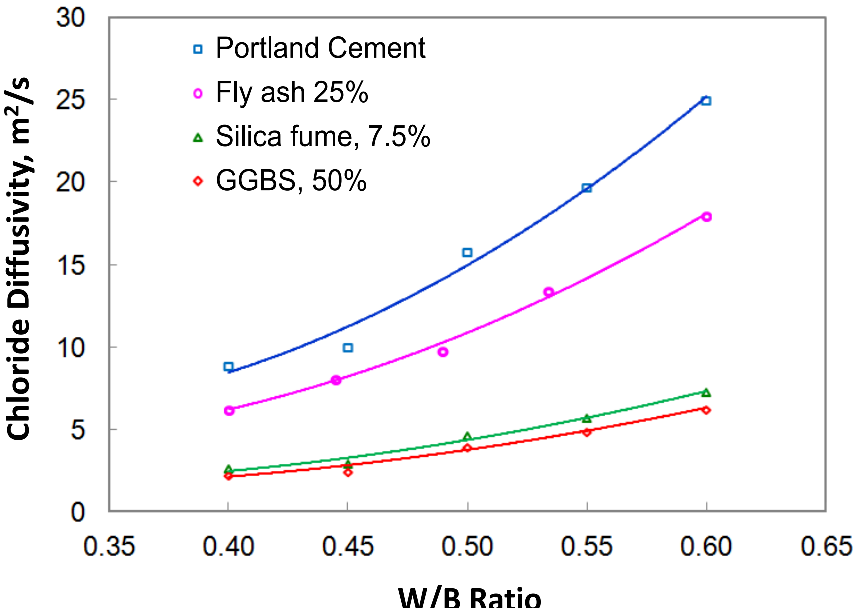
C_s	Surface chloride content，%
erfc	Complement error function
C_0	Initial chloride content，%
ΔX	Convection zone depth，m
D	Chloride diffusivity of concrete, m^2/s

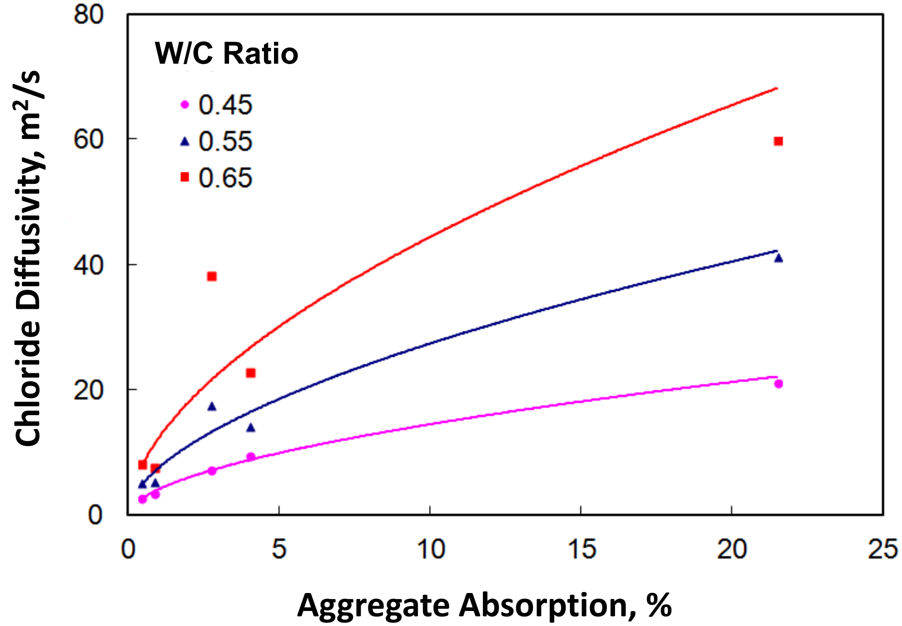
Significance: first time able to predict chloride concentration profile, marking the beginning of quantitative durability design.

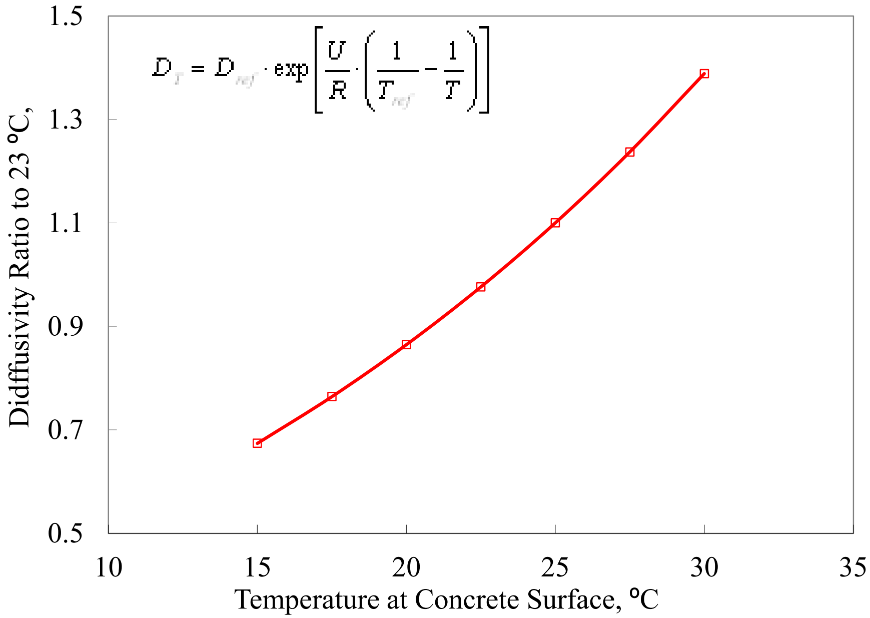
Limitation： only suitable for constant $\mathbf{C_s}$ content and constant **D**.

Collepardi, M., Marcialis,A., and Turriziani,R., Penetration of chloride ions into cement pastes and concrete, Journal of The American Concrete Society, Vol 55, No 10, Oct 1972

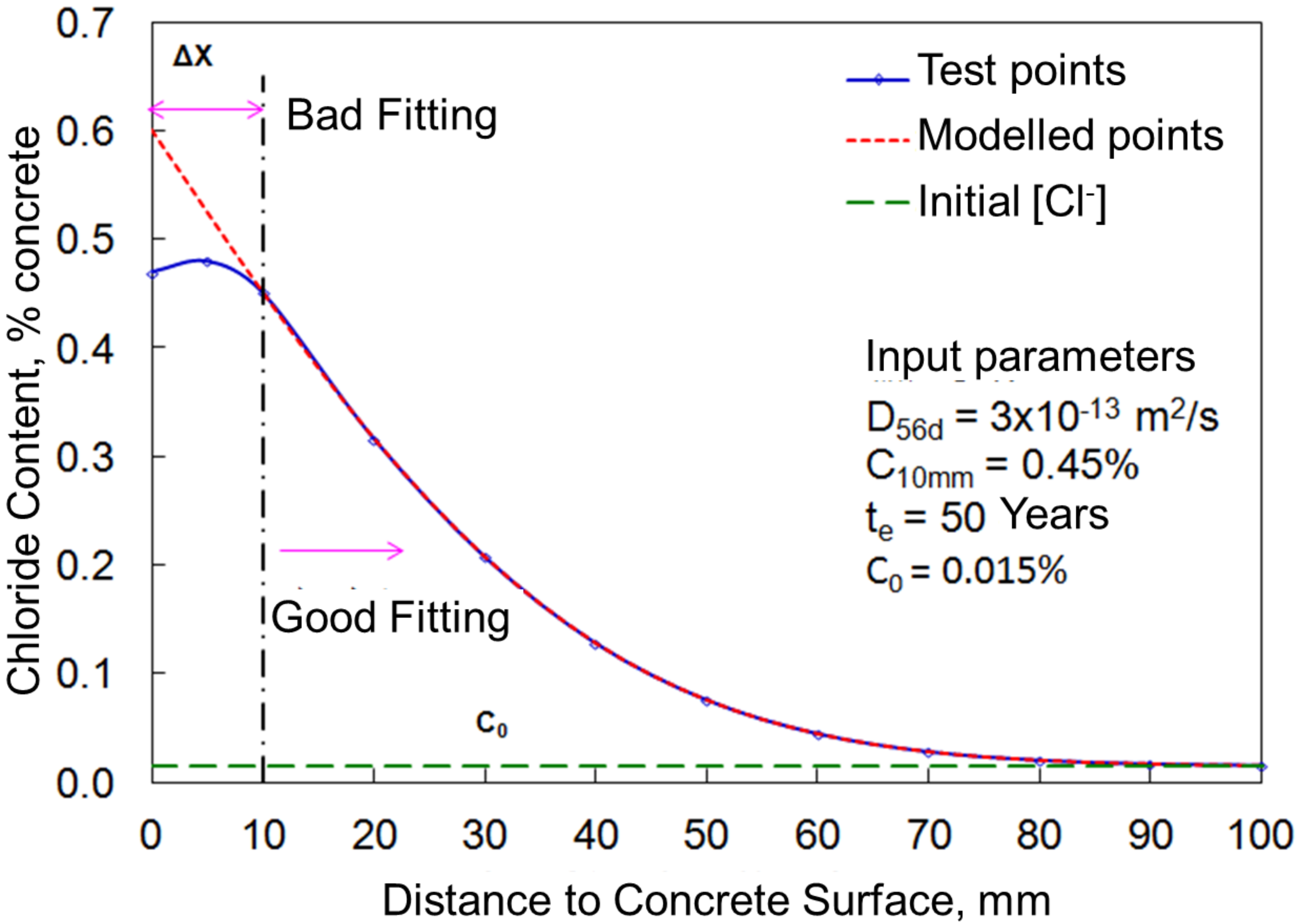
Factors Influencing Diffusivity







Chloride Modeling Example



Second Generation (2G) Analytical Chloride Model for Decreasing D_a – Solution to Fick's Second Law

Second Generation Model (Tang and Guilikers, 2007)

$$\frac{C-C_0}{C_s-C_0}=erfc\left[\frac{X-\Delta X}{2\sqrt{\frac{D_r}{1-m}\left[\left(1+\frac{t_{e0}}{t_e}\right)^{1-m}-\left(\frac{t_{e0}}{t_e}\right)^{1-m}\right]\left(\frac{t_r}{t_e}\right)^m t_e}}\right]$$

t_a	Concrete age
D_a	Instantaneous diffusivity (t_a)
t_r	Reference age
D_r	Reference diffusivity (t_r)
m	Age factor
t_e	Exposure time
t_{e0}	Age of starting exposure

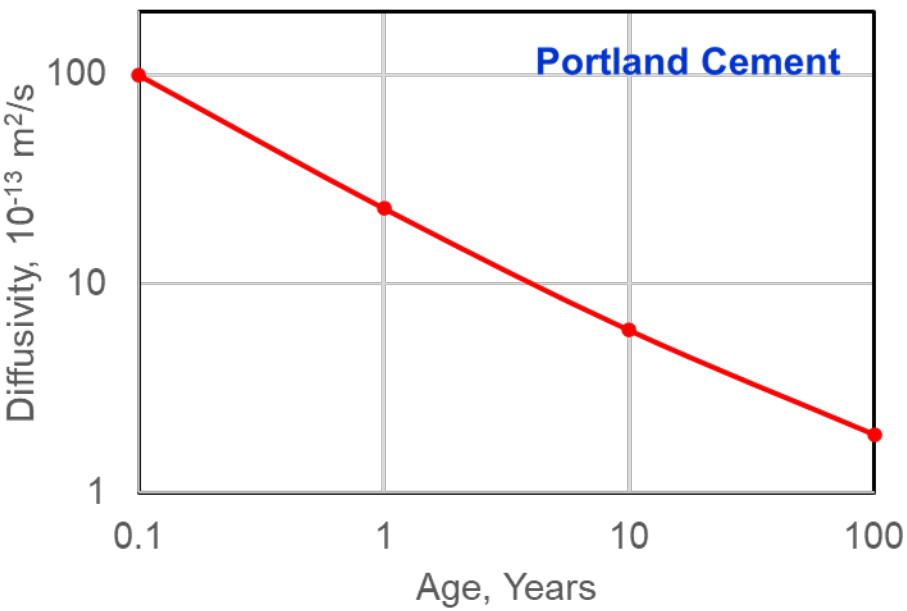
$$D_a = D_r\left(\frac{t_r}{t_a}\right)^m$$

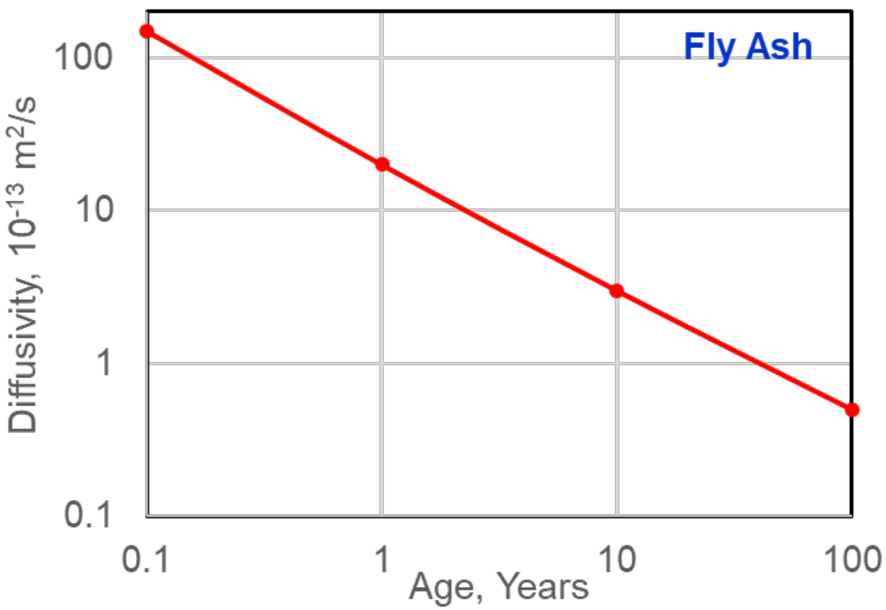
Significance: first time able to predict chloride profile with decreasing D_a

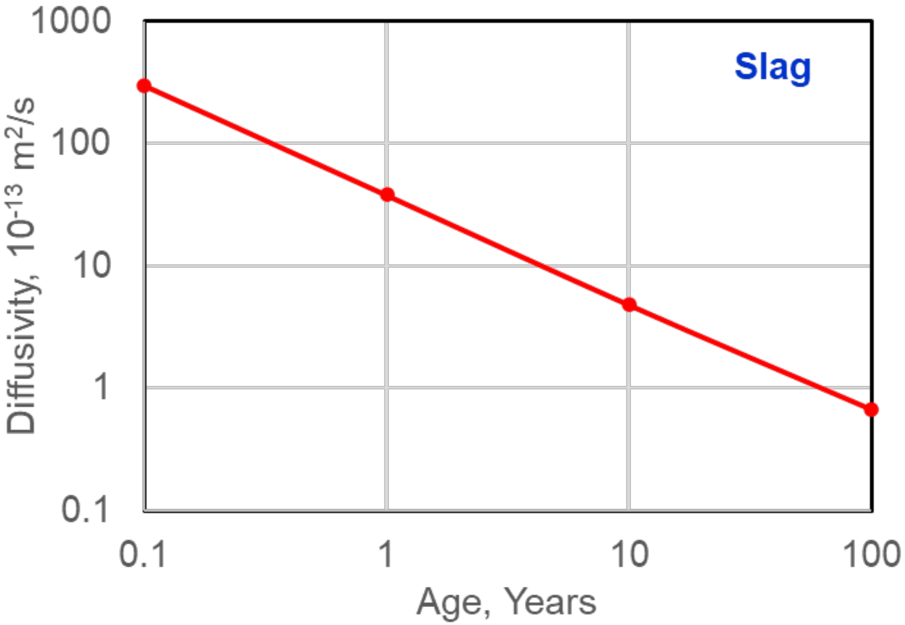
Limitations: Suitable only for constant S_c

Tang, L. and Gulikers, J., On the mathematics of time-dependent apparent chloride diffusion coefficient in concrete, Cement and Concrete Research, Volume 37, Issue 4, Pages 589-595, April 2007

Decrease of Diffusivity (D_a) with Age- Portland Cement







Bamforth, P., Price, W. F. and Emerson, M., An international review of chloride ingress into structural concrete, Transport Research Laboratory, Berkshire, UK, 1997

Age Factor (m) Input

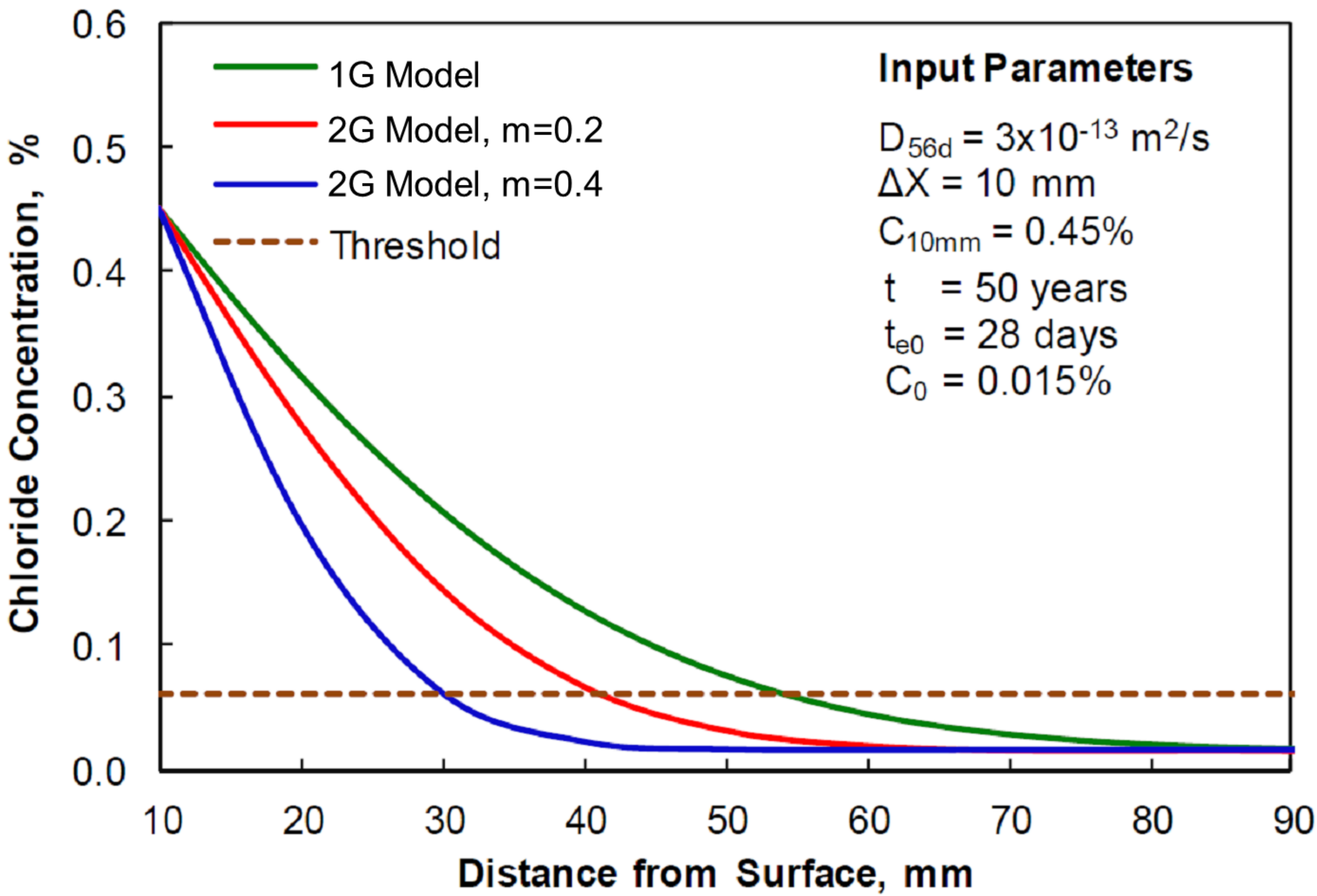
- Age factor is influenced by type of cementitious materials
- Fly ash and slag increase age factor due to late age hydration
- Age factor is often determined using following equation

$$m = 0.2 + 0.4 \cdot \left(\frac{\mathrm{FA}}{50} + \frac{\mathrm{GGBS}}{70}\right)$$

- FA is fly ash proportion, %
- GGBS is slag proportion, %

Ehlen, M.A, Life 365 v2 Users Manual, 2005,

Example of 2G Analytical Model Prediction



Empirical Chloride Model for Decreasing D_a

Second Generation Empirical Model (Bamforth, 2004),

$$\frac{C - C_0}{C_s - C_0} = erfc\left(\frac{X - \Delta X}{2\sqrt{D'_a t_e}}\right) = erfc\left(\frac{X - \Delta X}{2\sqrt{D'_r \left(\frac{t_r}{t_a}\right)^n t_e}}\right)$$

D'_a Apparent diffusivity, m^2/s,
D'_r Apparent reference diffusivity, m^2/s,
n Apparent age factor.

Features:

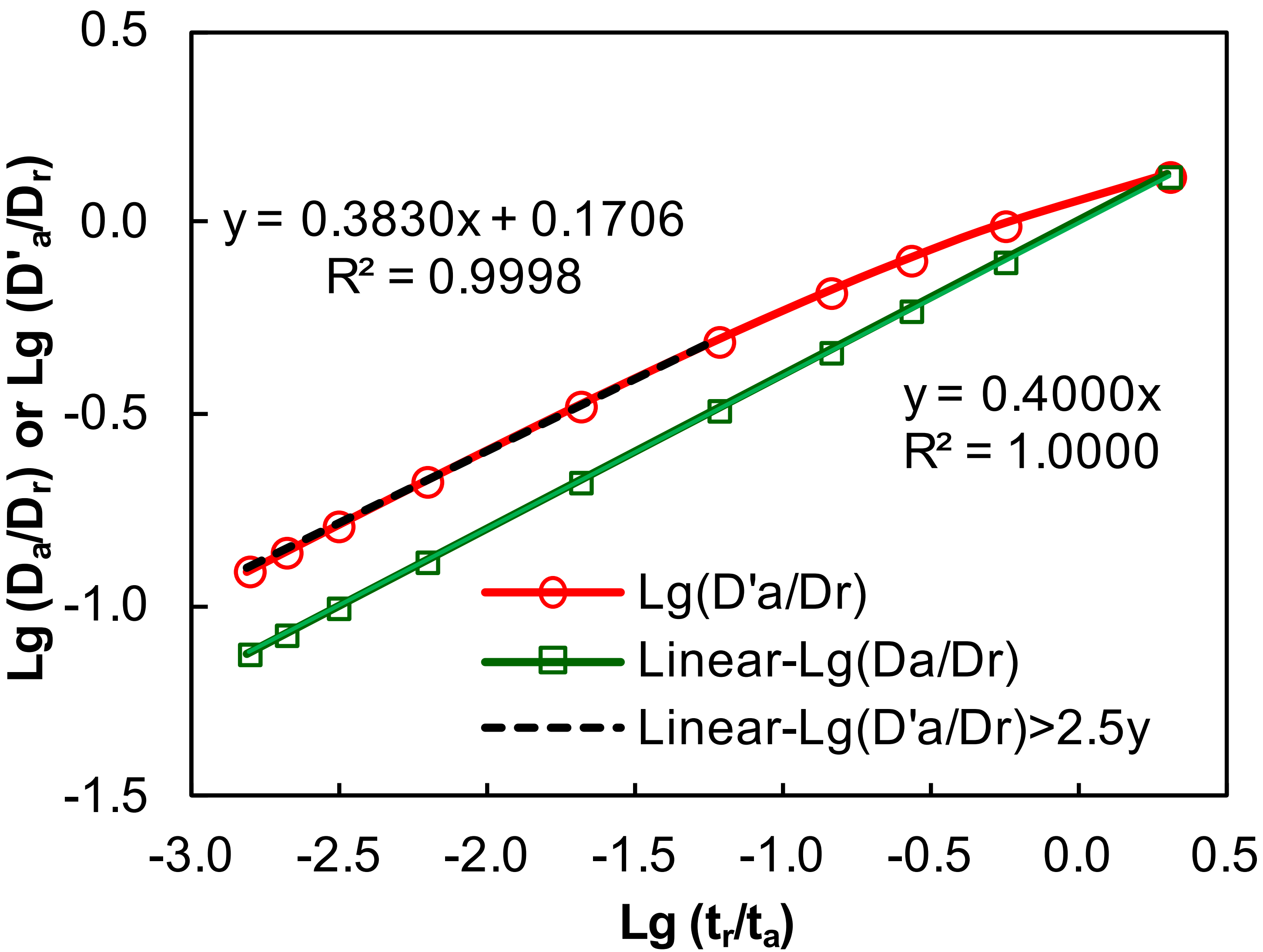
- Incorrect mathematic solution
- Diffusivity cannot be measured

Solutions:

- Use actual test data from structure
- Relationship with analytical model

Bamforth, P., Enhancing Reinforced Concrete Durability, Concrete Society Technical Report 61, The Concrete Society, Surrey, UK, 2004

Ratio of Diffusivities to Reference m=0.4



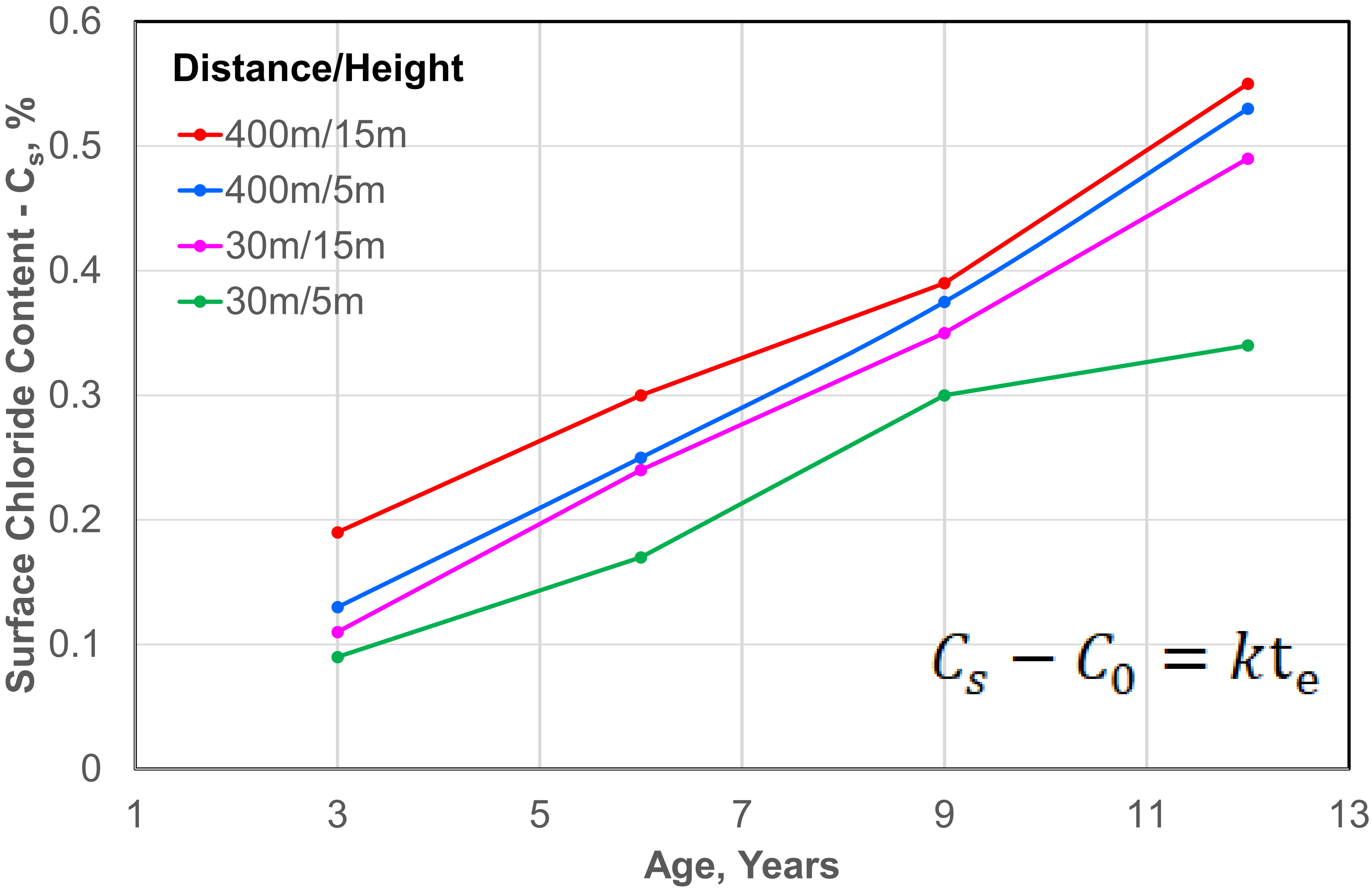
Zhou, S., Relationships of diffusivities and age factors between analytical and empirical chloride models for decreasing diffusivities, Proceeding of 14th Conference on Recent Advances in Concrete Technology and Sustainability Issues, 28 Oct-2 Nov 2018, Beijing, pp 55-66.

Age Factor + Diffusivity Inputs (Analytic vs Empirical)

m	n	D'_{56d}/D_{56d}	D'_{28d}/D_{28d}
0.1000	0.0979	1.10	1.09
0.2000	0.1947	1.21	1.20
0.3000	0.2900	1.34	1.33
0.4000	0.3830	1.48	1.46
0.5000	0.4729	1.64	1.61
0.6000	0.5584	1.82	1.77
0.7000	0.6382	2.00	1.92

Zhou, S., Relationships of diffusivities and age factors between analytical and empirical chloride models for decreasing diffusivities, Proceeding of 14th Conference on Recent Advances in Concrete Technology and Sustainability Issues, 28 Oct-2 Nov 2018, Beijing, pp 55-66.

Surface Chloride Linear Increase



Mustafa & Jusof, Atmosphere chloride penetration into concrete in semi-tropical marine environment, Cement and Concrete Research, Vol. 24, No. 4, 1994, pp661-670

Third Generation [3G] Analytical Model for Linear C_s

Linearly Increasing C_s and Decreasing D_a with time

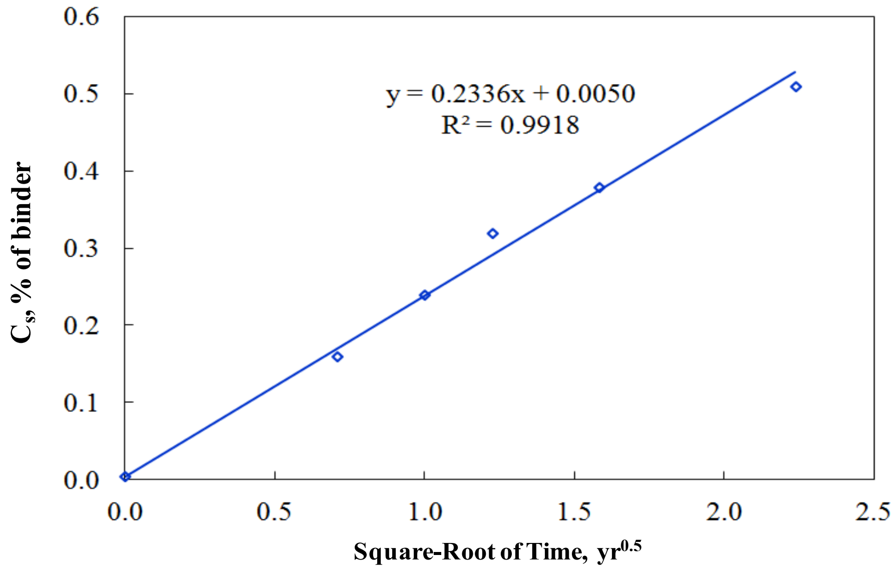
$$C' = C_0 + kt_e[(1+\frac{(X-\Delta X)^2(1-m)}{2D_r t_r^m[(t_e+t_{a0})^{1-m} - t_{a0}^{1-m}]})erfc(\frac{(X-\Delta X)\sqrt{1-m}}{2\sqrt{D_r t_r^m[(t_e+t_{a0})^{1-m} - t_{a0}^{1-m}]}})$$

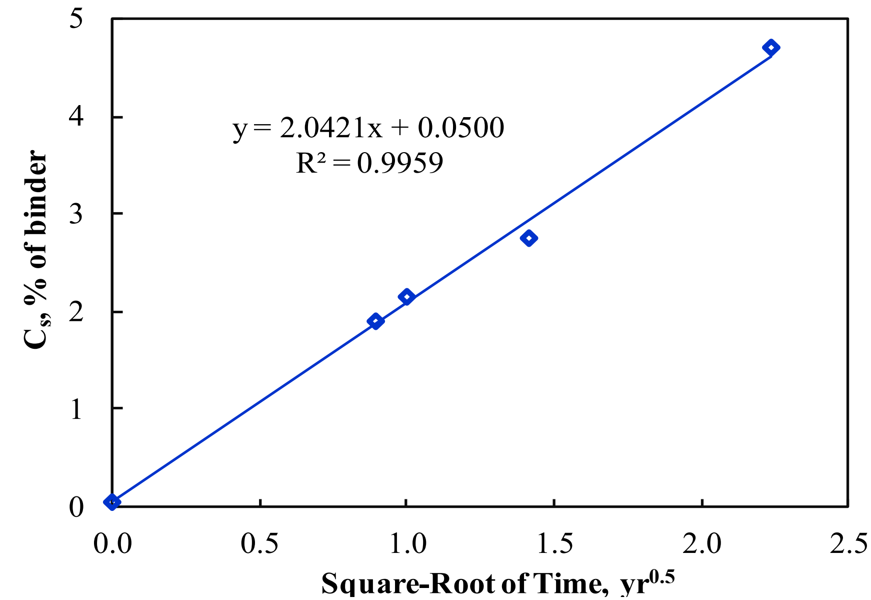
$$-\frac{(X-\Delta X)\sqrt{1-m}}{\sqrt{\pi D_r t_r^m[(t_e+t_{a0})^{1-m} - t_{a0}^{1-m}]}}Exp(\frac{-(X-\Delta X)^2(1-m)}{4D_r t_r^m[(t_e+t_{a0})^{1-m} - t_{a0}^{1-m}]})]$$

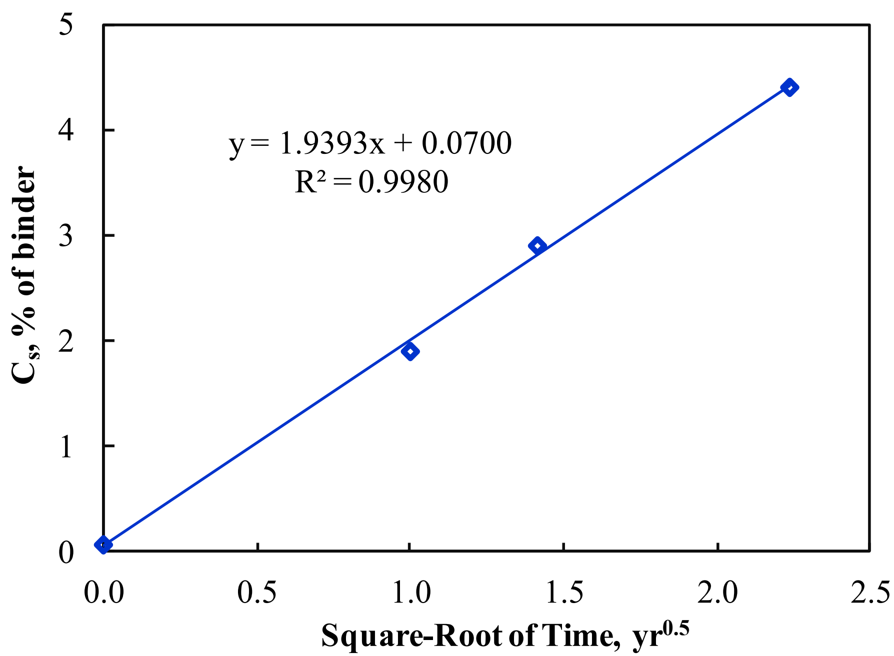
C' is the chloride concentration at a depth X

Zhou, S. Modeling chloride diffusion in concrete with linear increase of surface chloride, ACI Materials Journal, 111 (2014), **5**, pp 483-490.

C_s square-root increase with time







$$C_s - C_0 = k t_e^{0.5}$$

Zhou, S. Analytical model for square-root increase of surface chloride concentration and decrease of chloride diffusivity, J MCE , 2016, 28(4)

Third Generation [3G] Analytical Chloride Model for Square-root Cs

Square-root Increasing C_s and Decreasing D_a

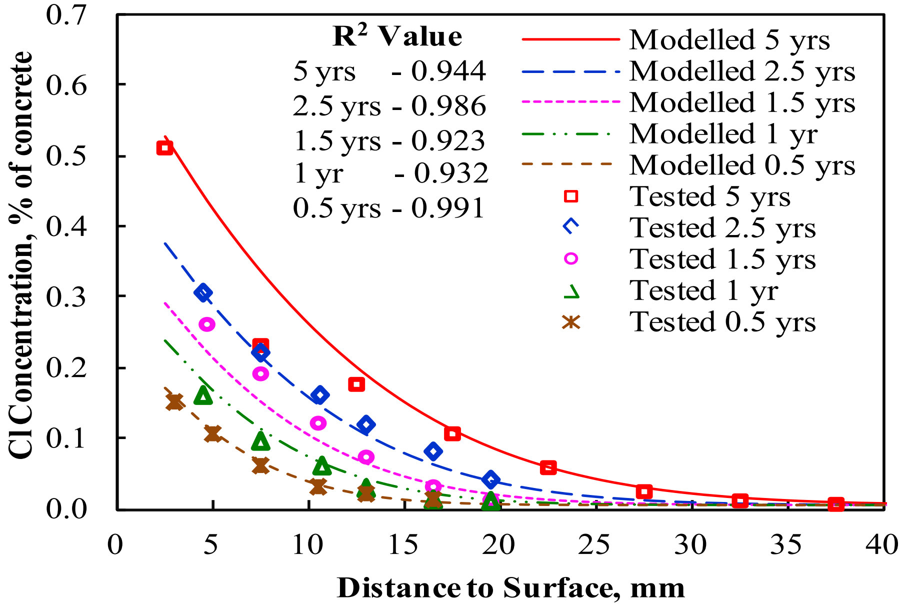
$$C' = C_0 + kt_e^{0.5}[Exp(\frac{-(X-\Delta X)^2(1-m)}{4D_r t_r^m[(t_e+t_{a0})^{1-m}-t_{a0}^{1-m}]}) - \frac{(X-\Delta X)\sqrt{\pi(1-m)}}{2\sqrt{D_r t_r^m[(t_e+t_{a0})^{1-m}-t_{a0}^{1-m}]}} \times$$

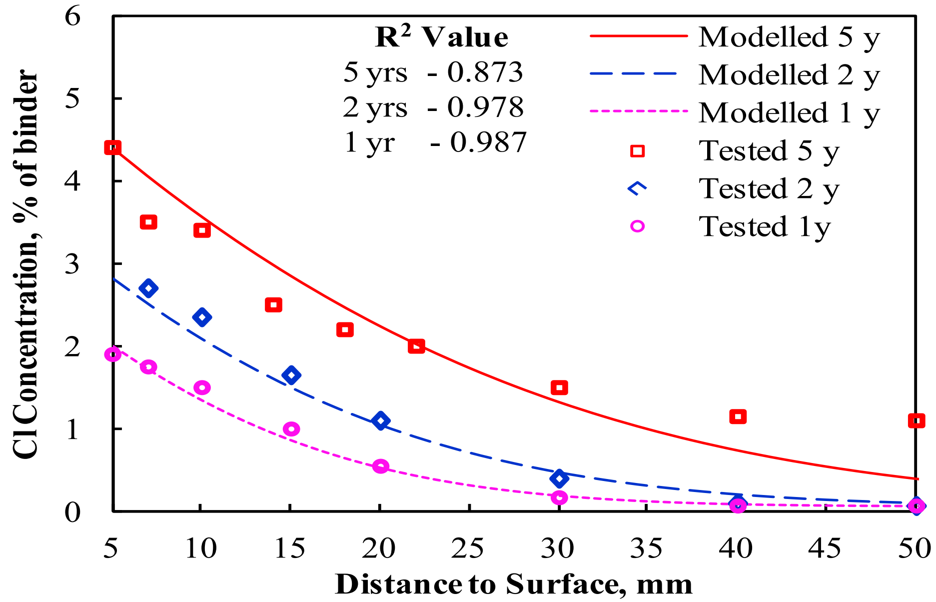
$$erfc(\frac{(X-\Delta X)\sqrt{1-m}}{2\sqrt{D_r t_r^m[(t_e+t_{a0})^{1-m}-t_{a0}^{1-m}]}})]$$

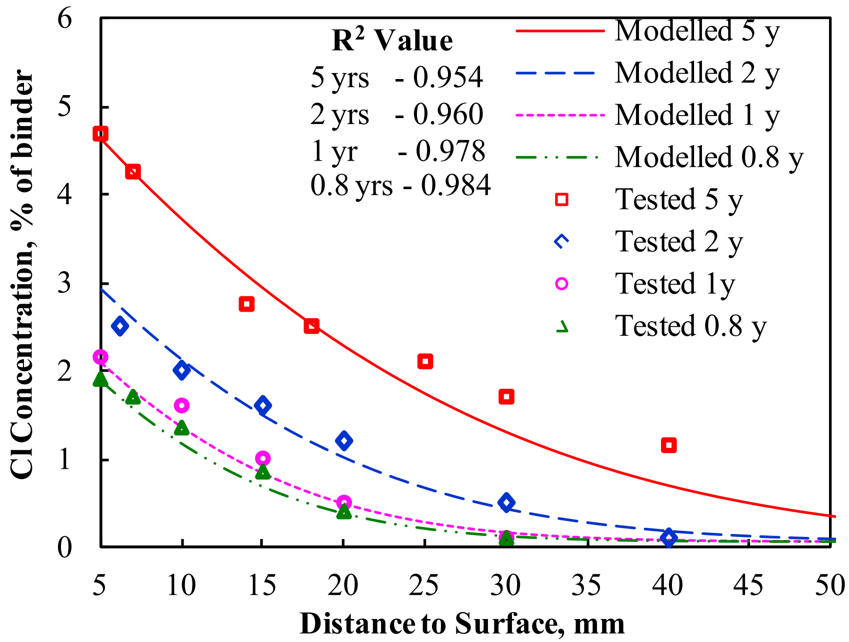
C' is the chloride concentration at a depth X

Zhou, S. Analytical model for square-root increase of surface chloride concentration and decrease of chloride diffusivity, J MCE , 2016, 28(4)

Validation of 3G Model for Square-root C_s

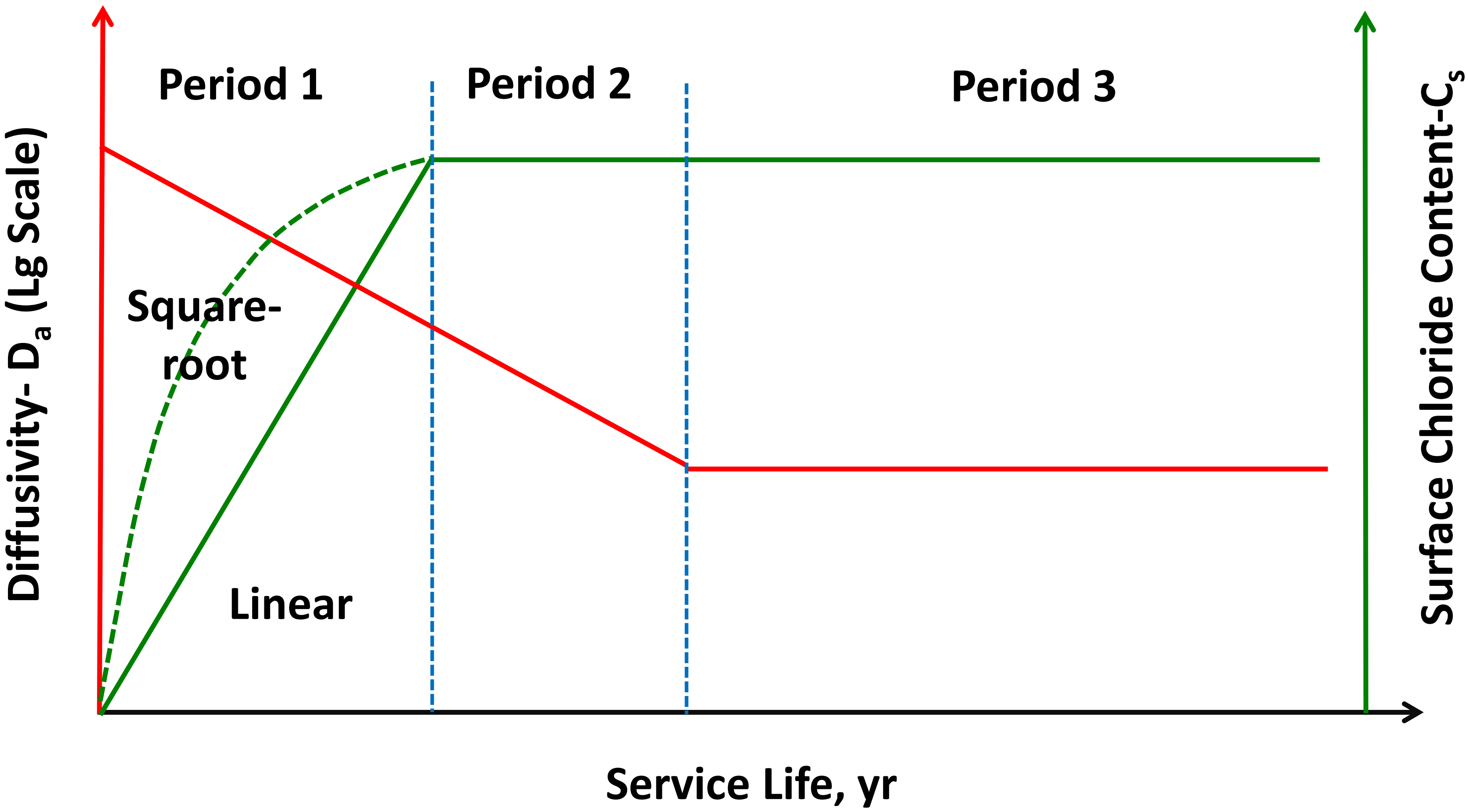




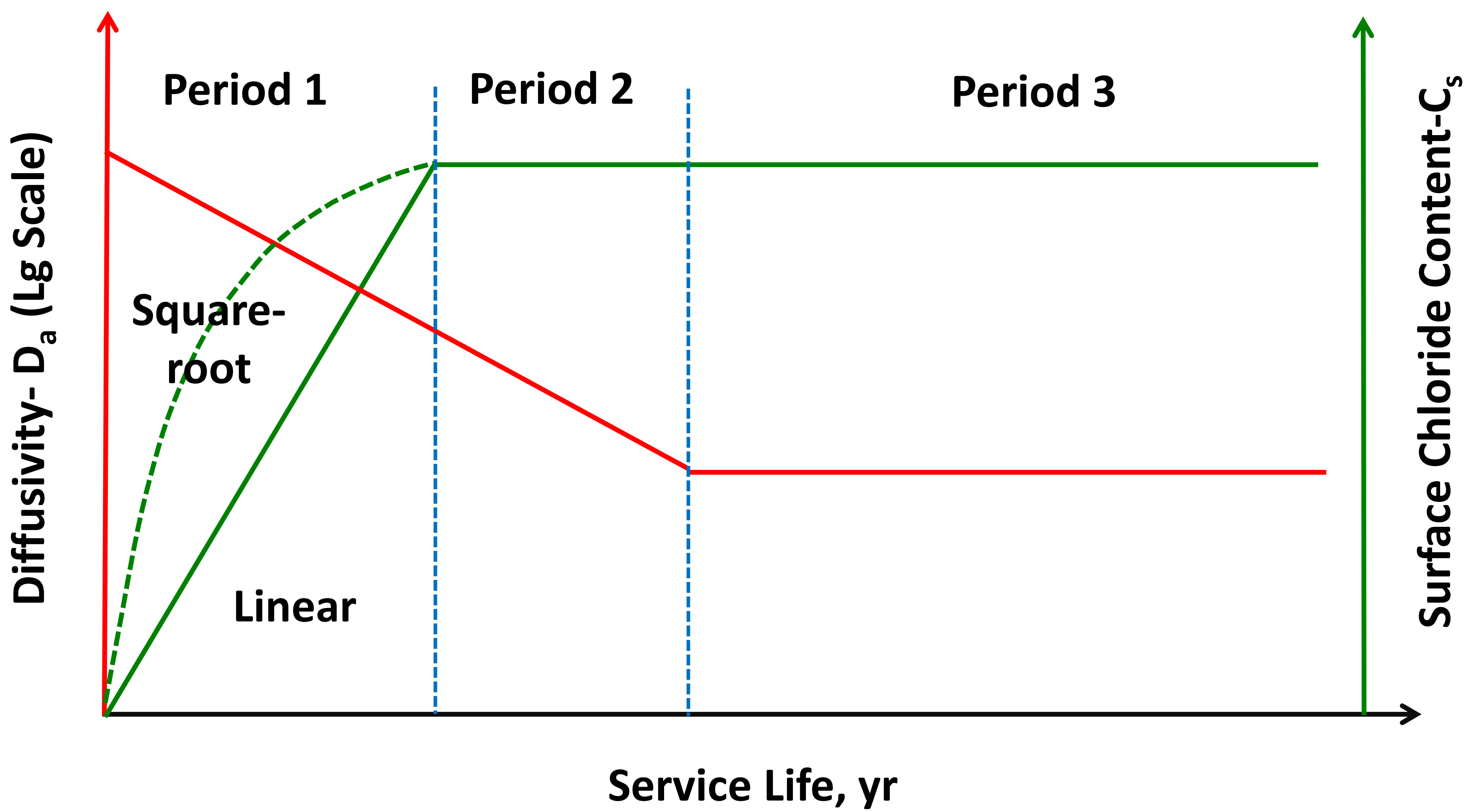


S. Zhou, Analytical model for square-root increase of surface chloride concentration and decrease of chloride diffusivity, Journal of Materials in Civil Engineering, 2016, 28(4)

3 Periods of changing surface chloride (C_s) and diffusivity (D_a)



3 Periods of changing surface chloride (C_s) and diffusivity (D_a)



Period 2 – Analytical Models for Decreasing D_a but Constant C_s

C_s Linear (Zhou, 2014):

$$C'' = C_0 + k t_{e1} erfc[\frac{(X-\Delta X)\sqrt{1-m}}{2\sqrt{D_r t_r^m [(t_e + t_{a0})^{1-m} - (\Delta t_e'' + t_{a0})^{1-m}]}}]$$

C_s Square-root (Zhou, 2016)

$$C'' = C_0 + k t_{e1}^{0.5} erfc[\frac{(X-\Delta X)\sqrt{1-m}}{2\sqrt{D_r t_r^m [(t_e + t_{a0})^{1-m} - (\Delta t_e'' + t_{a0})^{1-m}]}}]$$

$\Delta t_e''$ The time difference between Period 2 and 1 with matching chloride profiles.

Zhou, S., Modeling chloride diffusion in concrete with linear increase of surface chloride, ACI Materials Journal, 111 (2014), **5**, pp 483-490.

Period 3 – Analytical Models for Constant D_a and Constant C_s

C_s Linear (Zhou, 2014):

$$C''' = C_0 + kt_{e1} erfc[\frac{(X-\Delta X)\sqrt{(t_{e2}+t_{a0})^m}}{2\sqrt{D_r t_r^m (t_e - \Delta t_e''')}}]$$

C_s Square-root (Zhou, 2016)

$$C''' = C_0 + kt_{e1}^{0.5} erfc[\frac{(X-\Delta X)\sqrt{(t_{e2}+t_{a0})^m}}{2\sqrt{D_r t_r^m (t_e - \Delta t_e''')}}]$$

$\Delta t_e'''$ The time difference between Period 3 and 2 with matching chloride profiles.

Zhou, S., Modeling chloride diffusion in concrete with linear increase of surface chloride, ACI Materials Journal, 111 (2014), **5**, pp 483-490.

Partial Probability Chloride Modelling (BAE Method)

1. Profile of tested chloride data (for condition assessment- **C.A.**)
2. Modelling curve with 3G models (curve fitting for **C.A.**)
3. Distribution curve of tested or assumed cover & SD
4. Determine intersection of modelled curve with threshold line
5. Determine area percentage of cover distribution below intersection

Project 1 – New Design (N.D.) of a Train Tunnel in Mideast

1. Tunnels Details

Main Bored Section: shotcrete support, precast line, grouting annulus

Cut and Cover Box Section: cast in situ slabs, wall & roof slab

Underground Box Stations: cast in situ slabs, wall & roof slab

2. Exposure Conditions:

External: in groundwater containing a high level of chloride up to 163 g/l, which is 8 times of sea water.

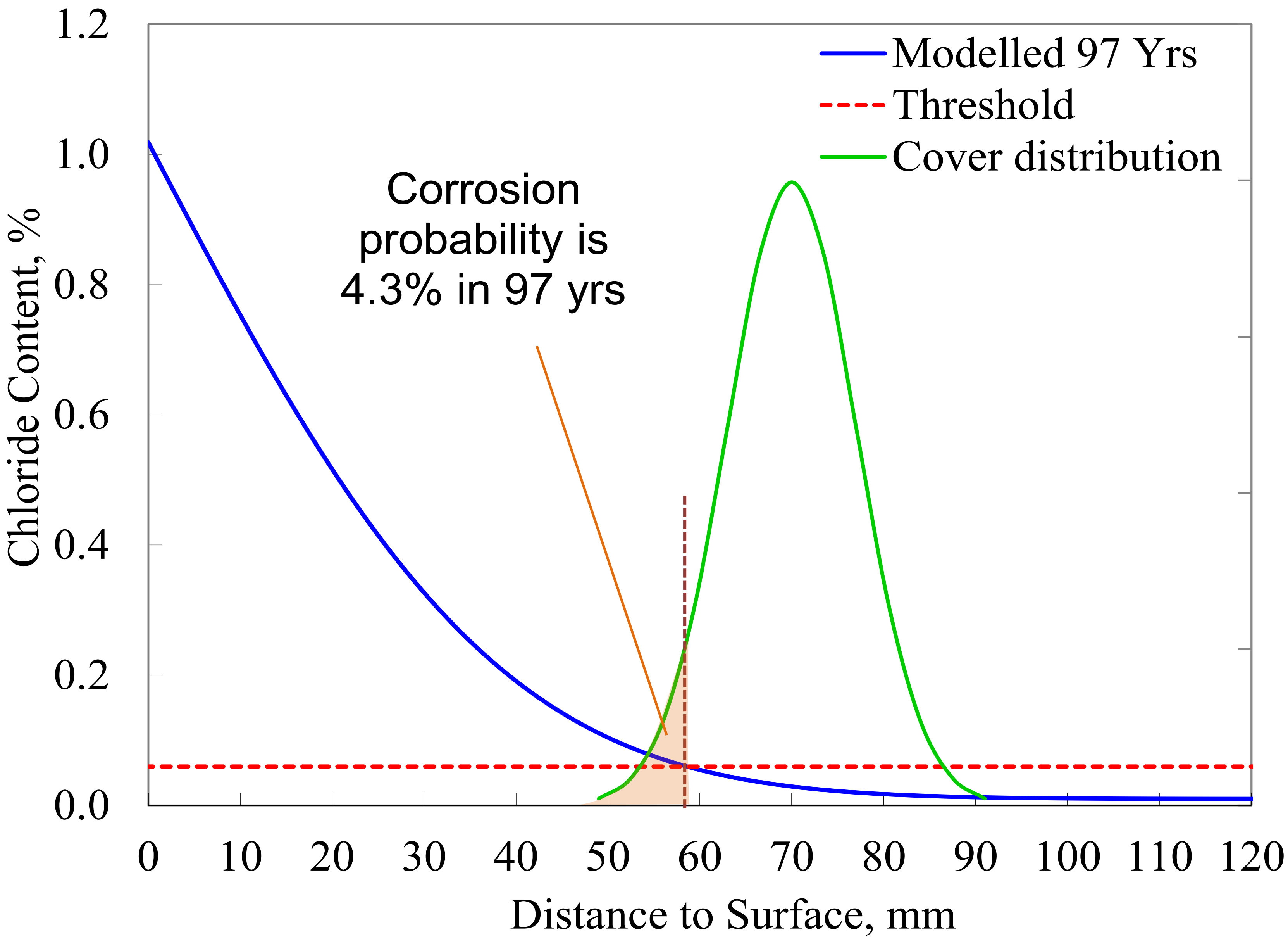
Internal: normal CO_2 with a high humidity.

Wicking: evaporation internally

Modeling Assumptions

1. **Design life:** 100 years
2. **Corrosion period:** 3 years
3. **Water chloride content:** 163 g/l
4. **Binder:** 25% FA+8% silica fume
5. **Diffusivity at 28 day:** 0.95×10^{-12} m^2/s
6. **Age factor:** 0.424
7. **Ultimate C_s:** 1.02% (based on porosity)
8. **Surface build-up pattern:** square-root
9. **Period 1 Ends:** 7.5 years
10. **Period 2 End:** 25 Years
11. **Surface temperature:** 27.5 ºC
12. **Design Cover:** 70 mm with SD of 7 mm

Chloride Modeling and Design Results



Project 2 – C.A. for a Mining Tunnel in Pacific

1. Tunnels Details

Tunnel section: corrugated steel section

Chamber Section: cast in situ slabs, wall & roof slab

2. Exposure Conditions:

External: in ground.

Internal:

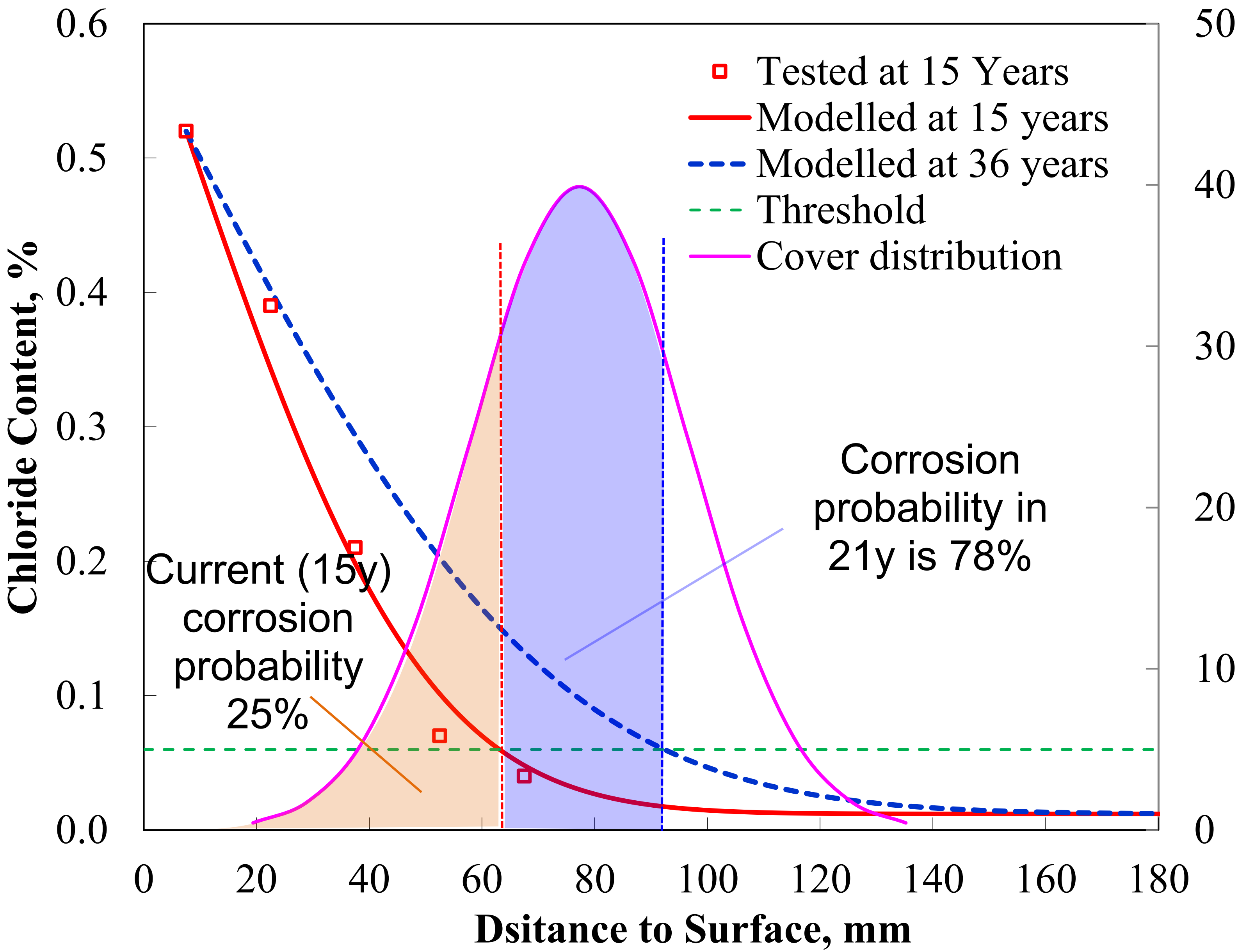
(1) Spraying of operation liquid containing seawater at a high temperature.

(2) Normal CO_2 with a high humidity.

Modeling Assumptions

1. **Design life:** 36 years
2. **Design Cover:** 77.3 mm with **SD** of 19.3 mm
3. **Binder:** Portland cement
4. **Age factor:** 0.2
5. **Surface build-up pattern:** square-root
6. **Period 1 Ends:** 7.5 years
7. **Period 2 Ends:** 25 Years
8. **Convection Zoon Depth:** 7.5 mm
9. **Ultimate C_s:** 0.52% (based on test results)
10. **Diffusivity at 28 day:** 3×10^{-12} m^2/s

Chloride Modeling Results



3, Carbonation Models and Application in Tunnel Elements

First Generation (1G) Carbonation Model

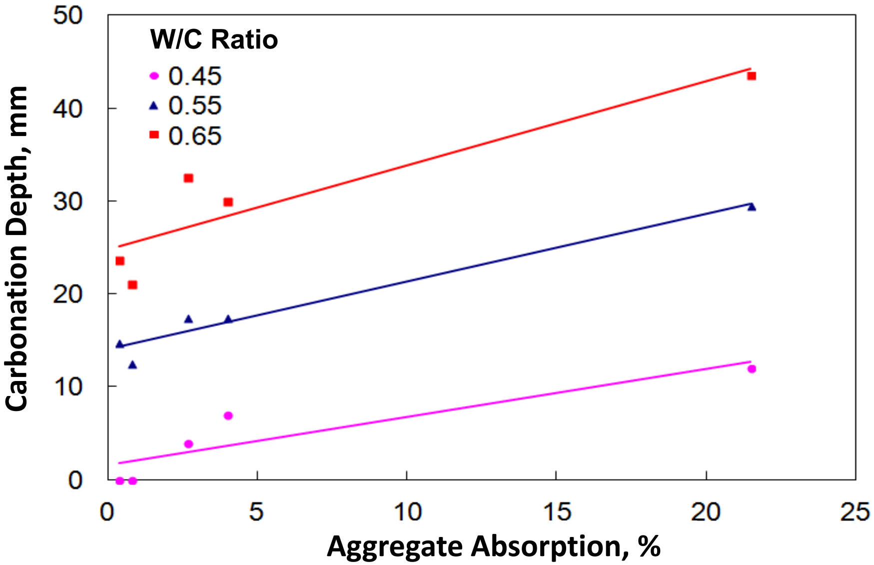
First Generation Model (Guirguis, 1987)

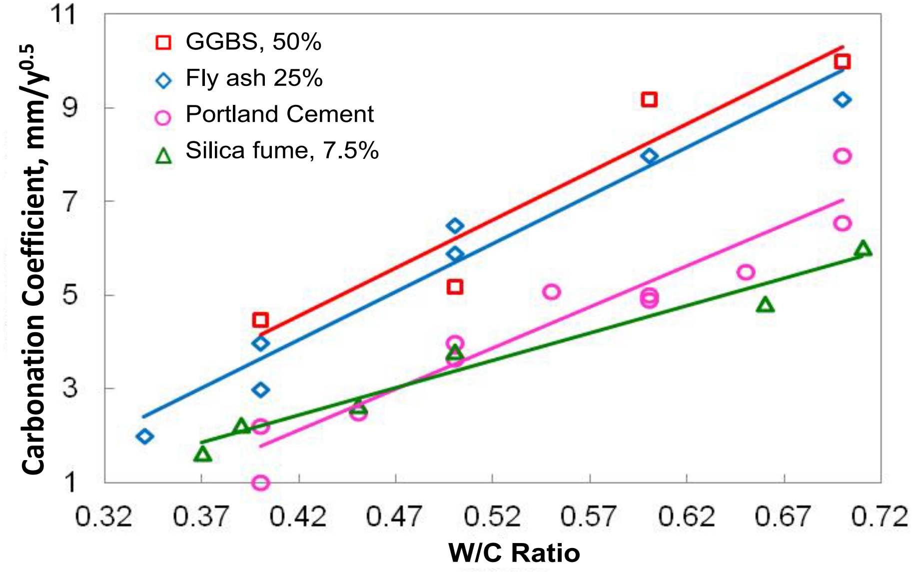
$$X = K \cdot \sqrt{t}$$

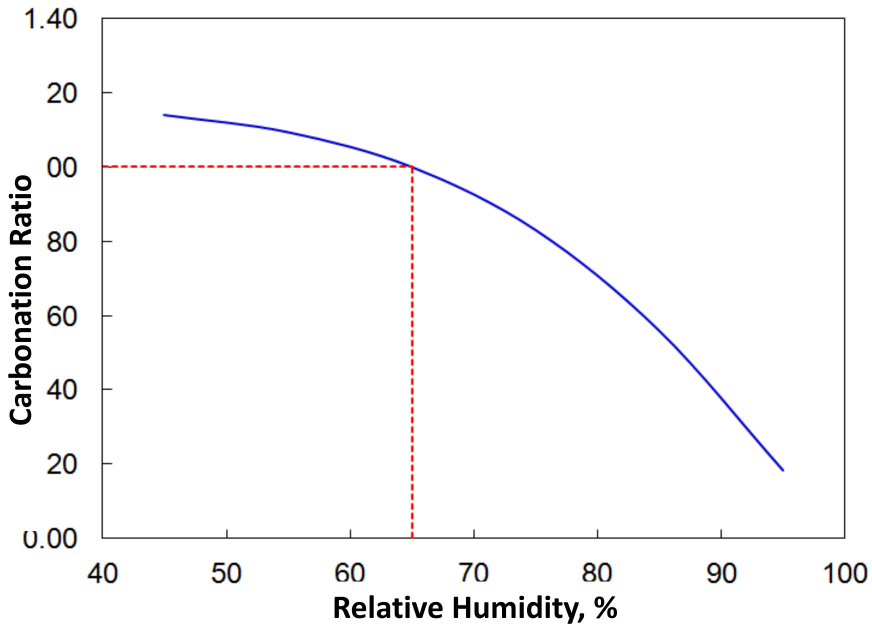
X	Carbonation depth
t	Exposure time
K	Carbonation coefficient

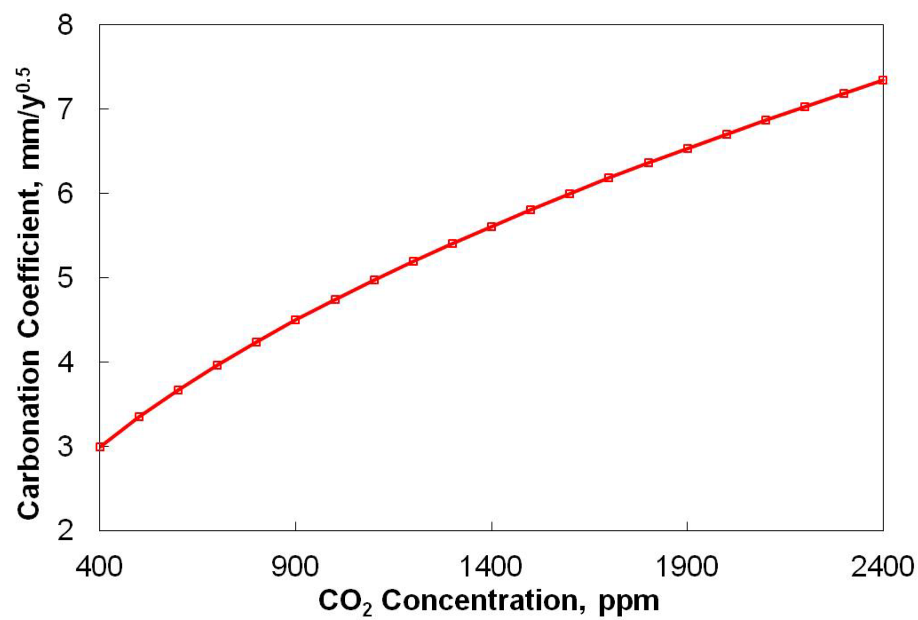
Guirguis, S., A basis for determining minimum cover requirement for durability, In: Concrete Durability, ACI Detroit, Michigan, 1987

Factors Influencing Carbonation









Second Generation (2G) Carbonation Model

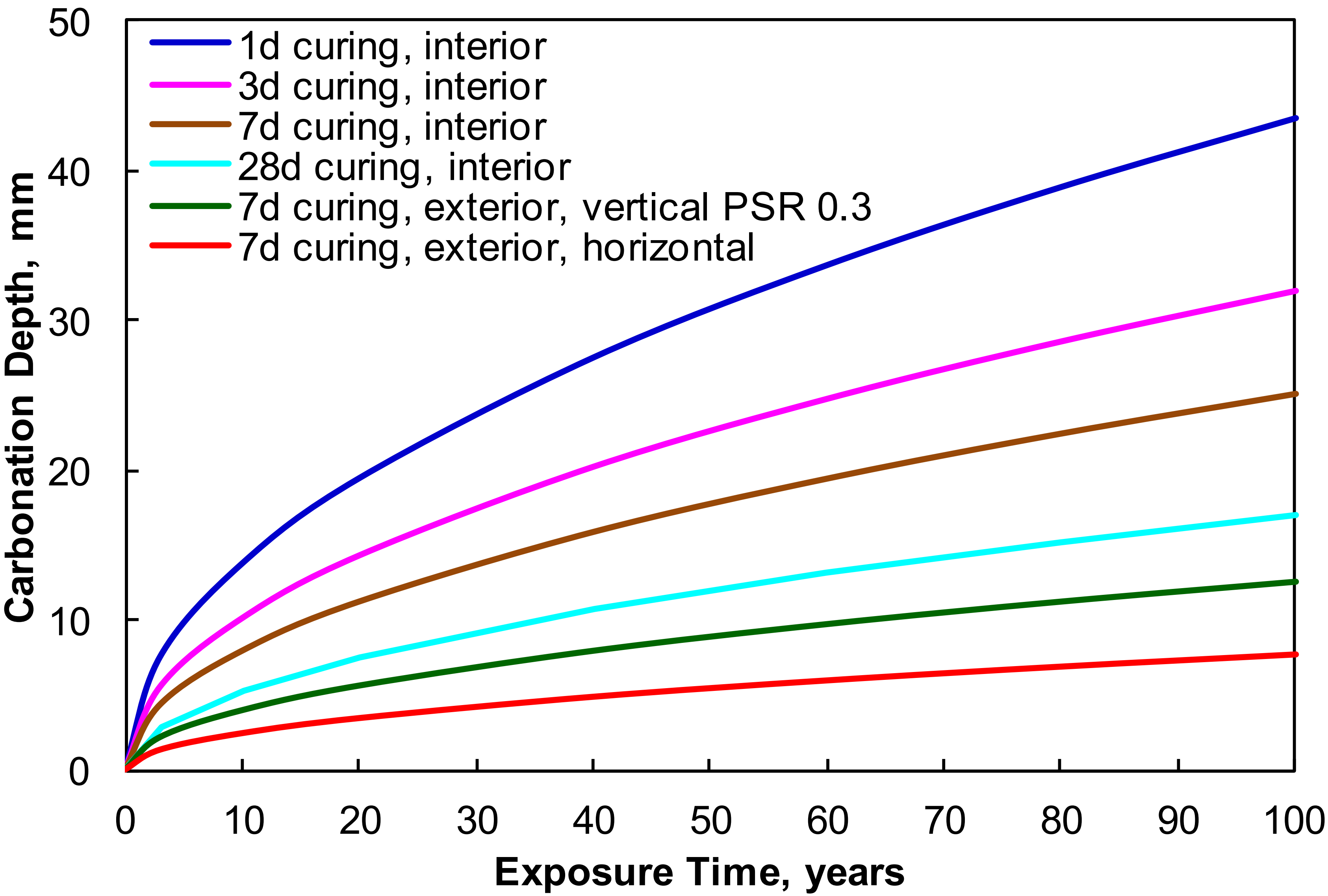
Modified *fib* Model (Zhou *et al*)

$$X = 40 \cdot k_{Indoor} \sqrt{k_e k_c C_s} \sqrt{t} \cdot W(t)$$

K_{indoor}	Indoor carbonation coefficient, $mm/y^{0.5}$
k_e	Humidity factor
k_c	Curing time factor
C_s	CO_2 concentration, kg/m^3,
$W(t)$	Weather factor

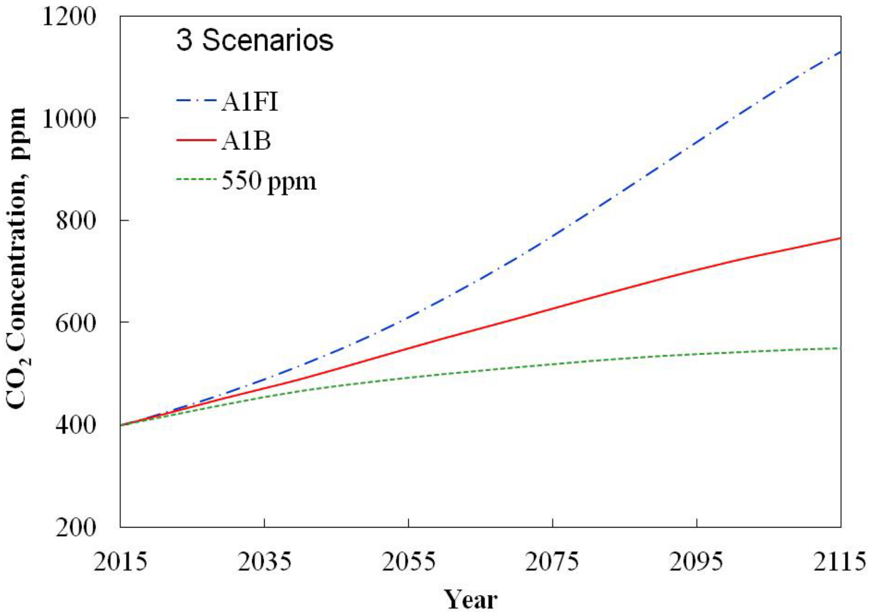
Zhou,S *et al*, Durability modelling of reinforcement corrosion in concrete structures, CIA Recommended Practice Draft, CIA, 2015

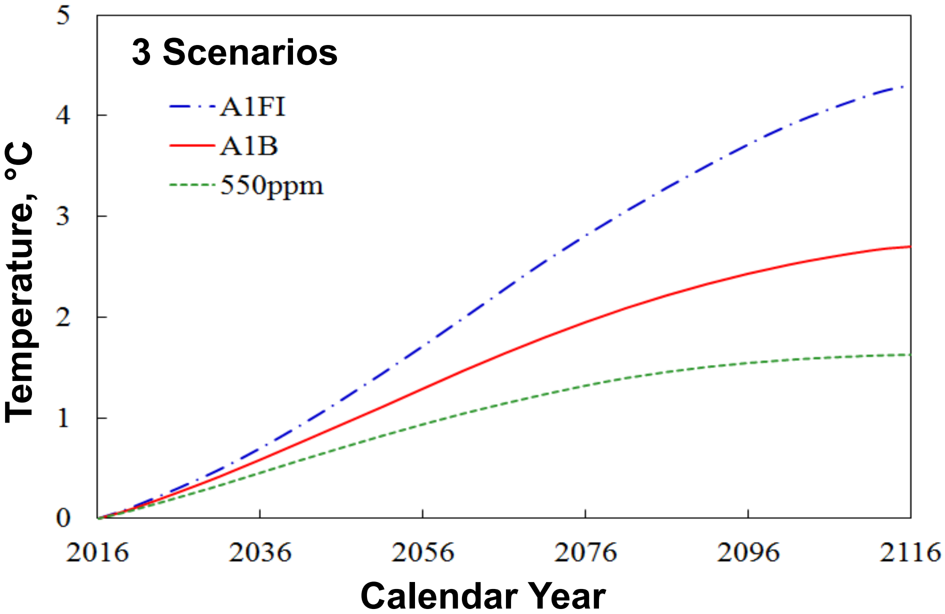
Modeling Example Using 2G Model

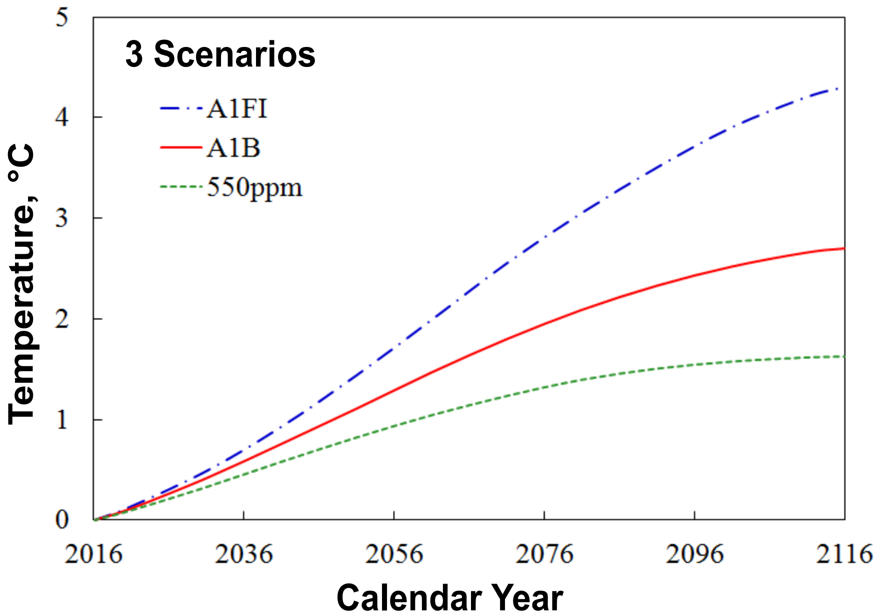


Zhou,S *et al*, Durability modelling of reinforcement corrosion in concrete structures, CIA Recommended Practice Draft, CIA, 2015

Climate Change (IPCC-2012)







IPCC (Intergovernmental Panel on Climate Change), Climate Change 2007 – the Fourth Assessment Report, Cambridge University, 2007

Third Generation (3G) Carbonation Model (Zhou, 2016)

$$X = t_0^{0.5(P_{SR}\cdot\frac{rain-days}{365})^{b_w}} \cdot \sqrt{2(\frac{t_c}{7})^{b_c}(k_t R_{ACC,0}^{-1} + \varepsilon_t) \cdot \left\langle C_s(t_0)^{0.5} \cdot \left[\frac{1-[0.01\cdot RH(t_0)]^{2.5}}{1-0.65^{2.5}}\right]^{2.5} \cdot e^{\frac{E}{2R}[\frac{1}{293}-\frac{1}{273+T(t_0)}]} \cdot t_{i+1}^{0.5\left[1-(P_{SR}\cdot\frac{rain-days}{365})^{b_w}\right]} + \sum_0^{n-1}\left\{\begin{array}{l} C_s(t_{i+1})^{0.5} \cdot \left[\frac{1-[0.01\cdot RH(t_{i+1})]^{2.5}}{1-0.65^{2.5}}\right]^{2.5} \cdot e^{\frac{E}{2R}[\frac{1}{293}-\frac{1}{273+T(t_{i+1})}]} \cdot \left[t_{i+1}^{0.5\left[1-(P_{SR}\cdot\frac{rain-days}{365})^{b_w}\right]} - t_i^{0.5\left[1-(P_{SR}\cdot\frac{rain-days}{365})^{b_w}\right]}\right] - \\ C_s(t_0)^{0.5} \cdot \left[\frac{1-[0.01\cdot RH(t_0)]^{2.5}}{1-0.65^{2.5}}\right]^{2.5} \cdot e^{\frac{E}{2R}[\frac{1}{293}-\frac{1}{273+T(t_0)}]} \cdot \left[t_{i+1}^{0.5\left[1-(P_{SR}\cdot\frac{rain-days}{365})^{b_w}\right]} - t_i^{0.5\left[1-(P_{SR}\cdot\frac{rain-days}{365})^{b_w}\right]}\right] \end{array}\right\}\right\rangle}$$

S Zhou, A numerical model for concrete carbonation under a gradually changing climate condition in future, Concrete in Australia, Vol. 42 No. 1, (Feb 2016) pp 45-52.

Terms in Model - 1

k_t	Regression parameter for test condition
$R^{-1}_{ACC,0}$	Inverse carbonation resistance $mm^2/year/kg/m^3$
ε_t	Regression interception test conditions $mm^2/year/kg/m^3$.
C_s	CO_2 concentration, kg/m^3
RH	Relative humidity, %.
t_c	Length of wet curing period, days.
b_c	Exponent of regression
t_0	Reference time

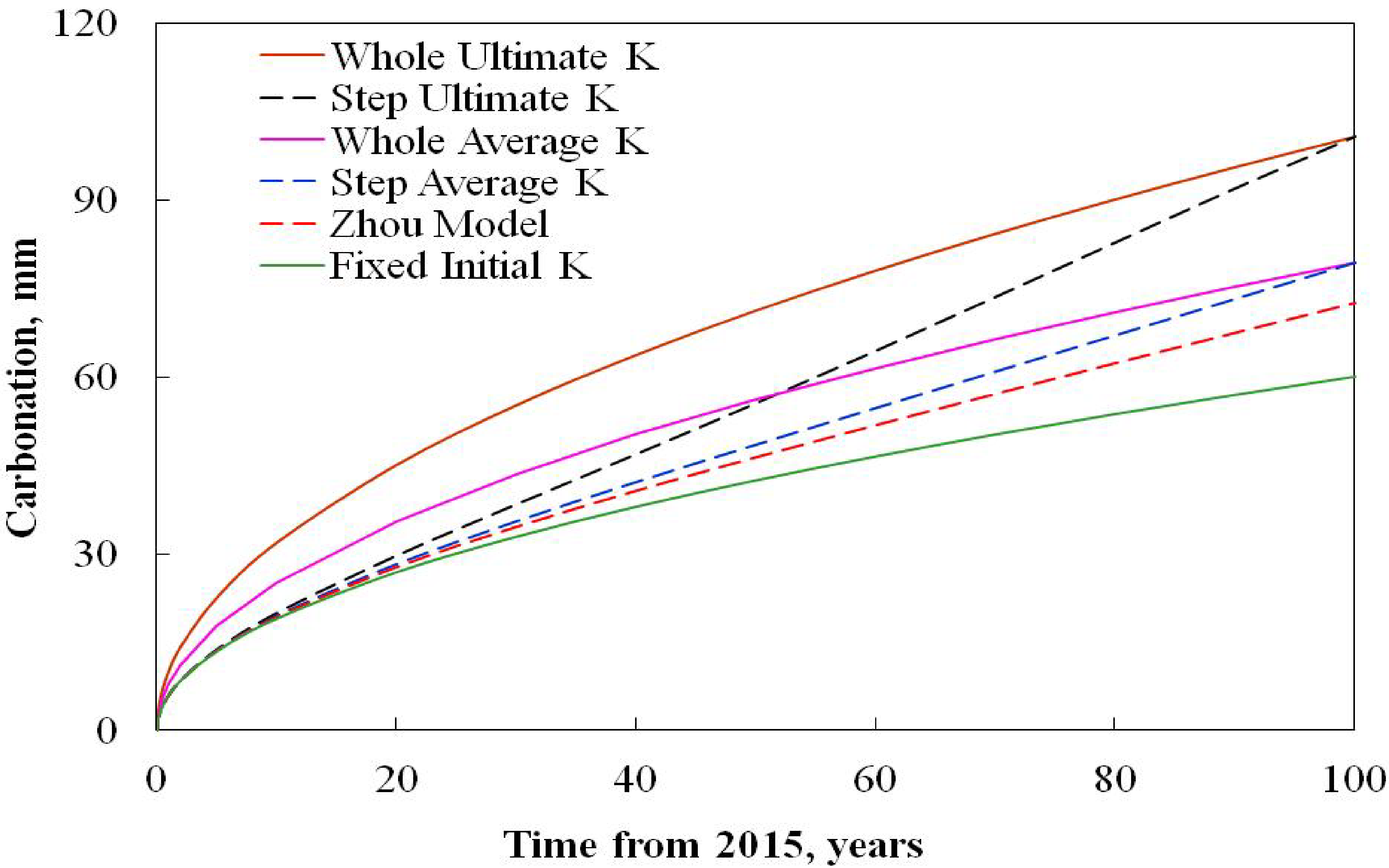
S Zhou, A numerical model for concrete carbonation under a gradually changing climate condition in future, Concrete in Australia, Vol. 42 No. 1, (Feb 2016) pp 45-52.

Terms in Model - 2

t	Exposure time, year
B_w	Exponent of regression
P_{SR}	Probability of driving rain
'rain-days'	Annual days >2.5 mm rain
t_i and t_{i+1}	Time sequence, yr
$C_{s(ti)}$ and $C_{s(ti+1)}$	CO_2 concentration, kg/m^3
$T_{(ti)}$ and $T_{(ti+1)}$	Temperatures, °C
$RH_{(ti)}$ and $RH_{(ti+1)}$	Relative humidity, %

S Zhou, A numerical model for concrete carbonation under a gradually changing climate condition in future, Concrete in Australia, Vol. 42 No. 1, (Feb 2016) pp 45-52.

Third Generation (3G) Models: Zhou's vs Earlier



S Zhou, A numerical model for concrete carbonation under a gradually changing climate condition in future, Concrete in Australia, Vol. 42 No. 1, (Feb 2016) pp 45-52.

Partial Probability Carbonation Modeling (BAE Models)

- Determine carbonation depth (for **C.A.**)
- Modelling curve with 3G models (tested for **C.A.** or assumed for **N.D.**)
- Plot covers distribution curve (tested for **C.A.** or assumed for **N.D.**)
- Determine overlapping area between cover and carbonation in current time (for **C.A.**)
- Determine overlapping area between cover and carbonation in future time

Project 1 – New Design (N.D.) of a Road Tunnel in Australia

1. Tunnels Details

Main Bored Section: shotcrete support, precast line, grouting annulus

Cut and Cover Box Section: cast in situ slabs, wall & roof slab

2. Exposure Conditions:

External: in groundwater containing a high level of chloride up to 15 g/l.

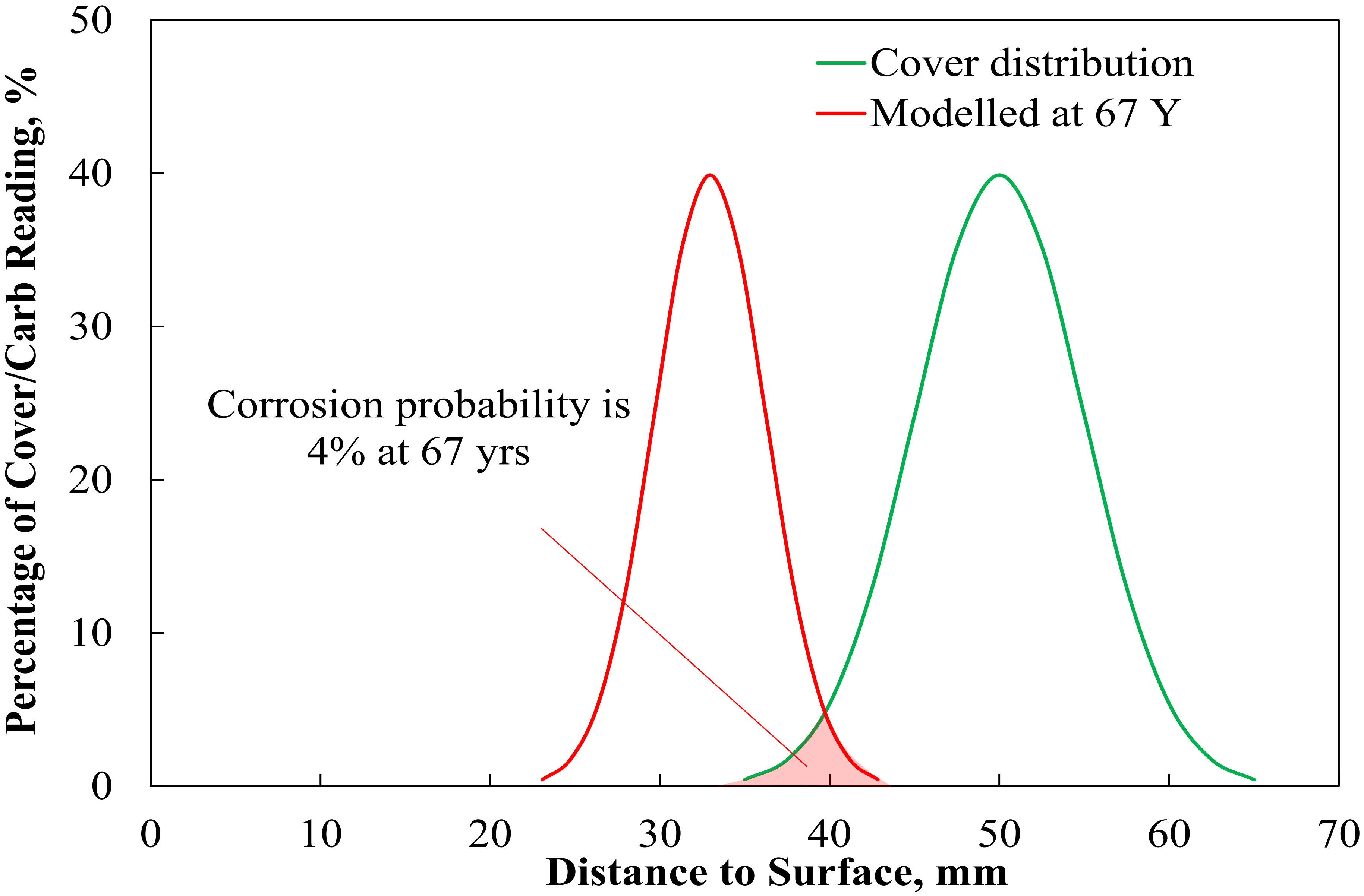
Internal: high CO_2,1400 ppm at two ventilation chimneys, low humidity

Wicking: evaporation internally

Modeling Assumptions

1. **Design life:** 100 years
2. **Corrosion period:** 31 years (estimation shown later)
3. **CO_2:** 1400 ppm
4. **Binder:** 8% silica fume
5. **W/B ratio:** 0.36
6. **Carbonation coefficient K_{indor}:** 1.4 $mm/y^{0.5}$ with CoV of 10% (R^{-1}_{ACC0}: 1000 mm^2/year/kg/m^3)
7. **Surface temperature:** 22.5 ºC
8. **Design Cover:** 50 mm with SD of 5 mm

Carbonation Modeling Results



Project 2 – C.A. for a Mining Tunnel in Pacific

1. Tunnels Details

Tunnel section: corrugated steel section

Chamber Section: cast in situ slabs, wall & roof slab

2. Exposure Conditions:

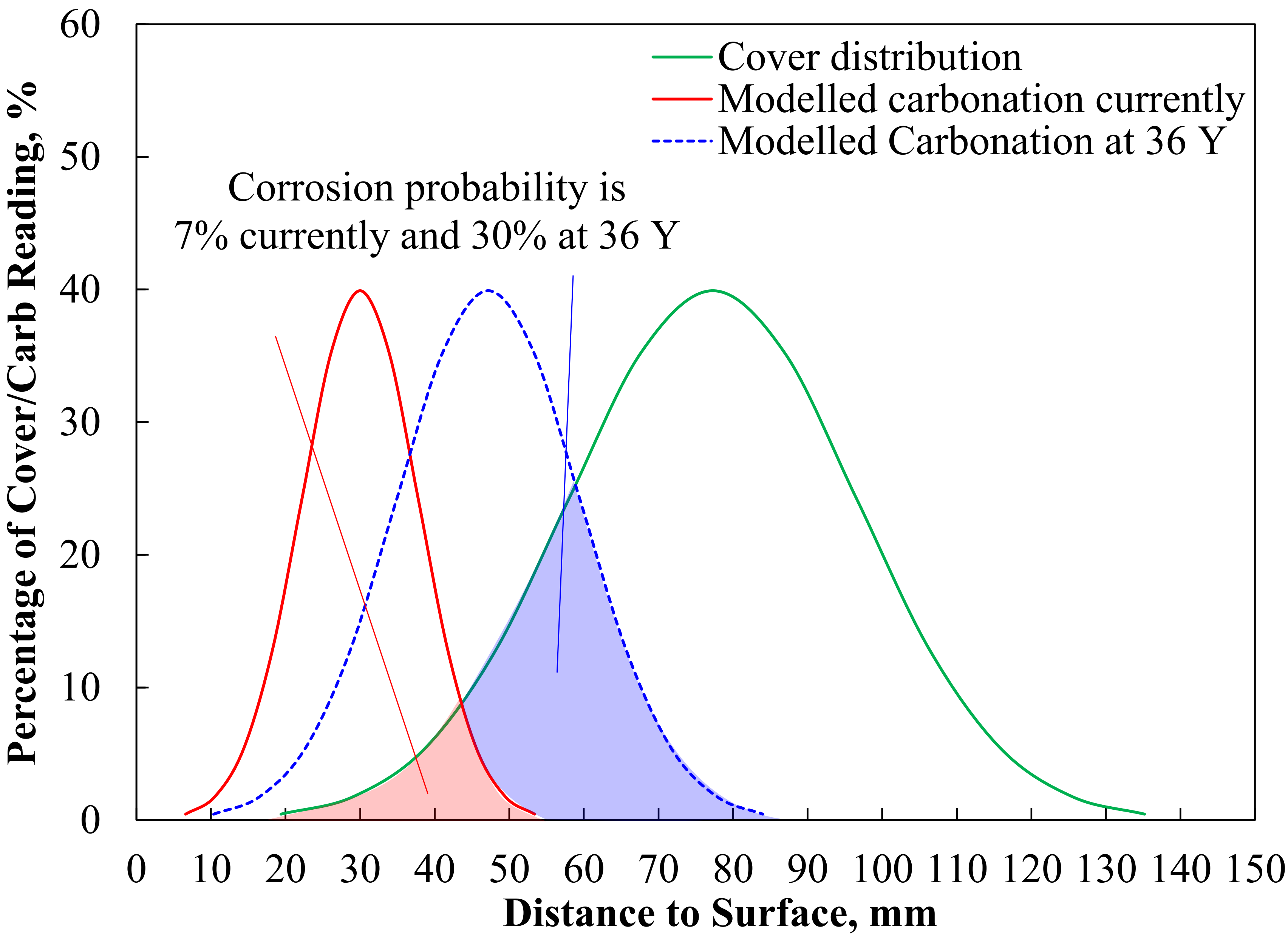
External: in ground.

Internal: Normal CO_2 with a high humidity.

Modelling Assumptions

1. **Current age: 15 years**
2. **Design life: 36 years**
3. **Carbonation tested: 30 mm with SD of 7.8 mm**
4. **Design Cover: 77.3 mm with SD of 19.3 mm**
4. **Initial CO_2: 364 ppm**
5. **Carbonation coefficient K_{indor}: 11.3 mm/$y^{0.5}$** (R^{-1}_{ACC0}: **82075 mm^2/year/kg/m^3**)

Carbonation Modelling Results



4, Rebar Corrosion Modelling and Application

Reinforcement Corrosion Rate (DuraCrete, 1998)

a) Chloride-induced rebar corrosion

Condition	Corrosion Rate, μm/y
Wet-rarely dry	4
Wet-dry	30
Airborne chloride	30
Immersed permanently	Unless poor quality， 0
Tidal	70

b) Carbonation-induced rebar corrosion

Condition	Corrosion Rate, μm/y
Dry	0
Wet-rarely dry (unsheltered)	4
Medium humidity (sheltered)	2
Wet-dry (unsheltered)	5

DuraCrete, Modelling of Degradation - Probabilistic Performance Based Durability Design of Concrete Structures, EU - Brite EuRam III, Contract BRPR-CT95-0132, Project BE95-1347/R4-5, December pp 174, 1998.

Corrosion Depth and Time

Limit of Rebar Corrosion Depth (Webster, 2000)

$$\delta_{CR} = 1.25 \cdot C$$

δ_{CR} Limit of corrosion depth (crack 0.1mm), μm

C Concrete cover, mm

Rebar Corrosion Time

$$T_1 = \frac{\delta_{CR}}{R_{corr}}$$

T_1 Reinforcement Corrosion Time, y

R_{corr} Corrosion rate, μm/y

Webster, M.P., The assessment of corrosion-damaged concrete structures, PhD Thesis to University of Birmingham, Birmingham, UK, 2000

Chloride-Induced Rebar Corrosion - Project 1

Rebar Corrosion Depth:

$$\delta_{CR} = 1.25 \cdot C$$

$$= 1.25 \times 70 = 87.5\ \mu m$$

Corrosion Propagation Time:

$$T_1 = \frac{\delta_{CR}}{R_{corr}}$$

$$= \frac{87.5}{30} = 2.9 \approx 3\ y$$

Corrosion Induction (Chloride Ingress) Time:

$$T_0 = 100 - T_1$$

$$\approx 100 - 3 \approx 97\ y$$

Carbonation-Induced Rebar Corrosion – Example 1

Rebar Corrosion Depth:

$$\delta_{CR} = 1.25 \cdot C$$

$$= 1.25 \times 50 = 62.5\ \mu m$$

Corrosion Propagation Time:

$$T_1 = \frac{\delta_{CR}}{R_{corr}}$$

$$= \frac{62.5}{2} = 31.25 \approx 31\ y$$

Corrosion Induction (Carbonation) Time:

$$T_0 = 100 - T_1$$

$$\approx 100 - 31 \approx 69\ y$$

The End

Questions?

Thanks.