Workshop on Service Life of Concrete Structure
-Concept and Design-

Service Life Prediction of Cracked Reinforced Concrete Structures subjected to Chloride Attack and Carbonation

4 Feb. 2005
Sapporo, Japan

H.-W. Song

Professor
School of Civil and Environmental Engineering
Yonsei Univ., Seoul 120-749, KOREA

Outline

Introduction

Durability concept

- *Durability concept and strategy*
- *Performance-based durability design*
- *Scheme of service life prediction*

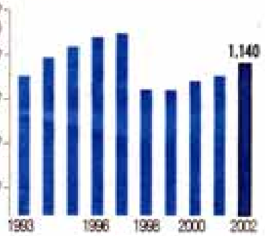
Models for service life prediction

- *Early-age cracks in concrete*
- *Chloride diffusion-penetration model*
- *CO_2 carbonation model*
- *Steel corrosion model*
  - *Electric corrosion cell model*
  - *Oxygen diffusion model*
- *Corrosion cracking model*

Examples for Service life prediction

Conclusion

Korean daily newspapers warning durability problems of concrete structures



중앙일보 2003년 3월 24일 월요일 40판 사 회

부실공사·난개발로 툭하면 헐고 다시 지어

한국은 '콘크리트 공화국'

인천시 서구 수도권 쓰레기 매립지에는 건설폐기물을 가득 실은 15t 트럭이 뿌연 먼지를 일으키며 하루 8백여대씩 줄을 서서 들어온다. 쓰레기 종량제로 생활쓰레기는 크게 줄었지만 콘크리트 등 건설폐기물은 지난해 수도권 매립지 전체 반입 쓰레기의 53%를 차지했을 정도로 갈수록 늘고 있다.

매립지 앞 네곳의 건설폐기물 중간처리업체마다 잘게 부순 폐콘크리트 가루가 산더미처럼 쌓여 있다. ㈜삼력환경의 진재흥(陳載洪)상무는 "재활용 골재를 일정 비율 의무적으로 사용토록 해야 하는데도 건설교통부·환경부 등 부처 간 이견으로 이뤄지지 않고 있다"고 말했다.

이곳의 '폐콘크리트 사태(沙汰)'는 앞으로도 계속될 전망이다.

시멘트 1인당 소비 세계평균의 4배

시민·환경단체들은 "지은 지 얼마 되지도 않은 아파트를 재건축하고 해마다 수해복구 공사가 반복되기 때문에 시멘트 소비량이 많다"고 주장하고 있다.

또 건설폐기물 재활용을 통해 모래·자갈 등 골재 부족을 해결하고 환경 훼손도 줄이자고 제안했다.

한국의 시멘트 소비량은 97년 1천3백43kg까지 증가했다가 외환위기로 99년에는 9백59kg까지 줄었으나 그 후 다시 왕성하게 회복하고 있다. 국가 전체로 따져도 한국의 시멘트 생산·소비량은 모두 세계 5위다.

인하대 서병하(徐柄夏·토목공학과)교수는 "우리나라는 기후변화가 매우 심하기 때문에 목재보다 콘크리트를 쓸 수밖에 없는 경우가 많다"고 말했다.

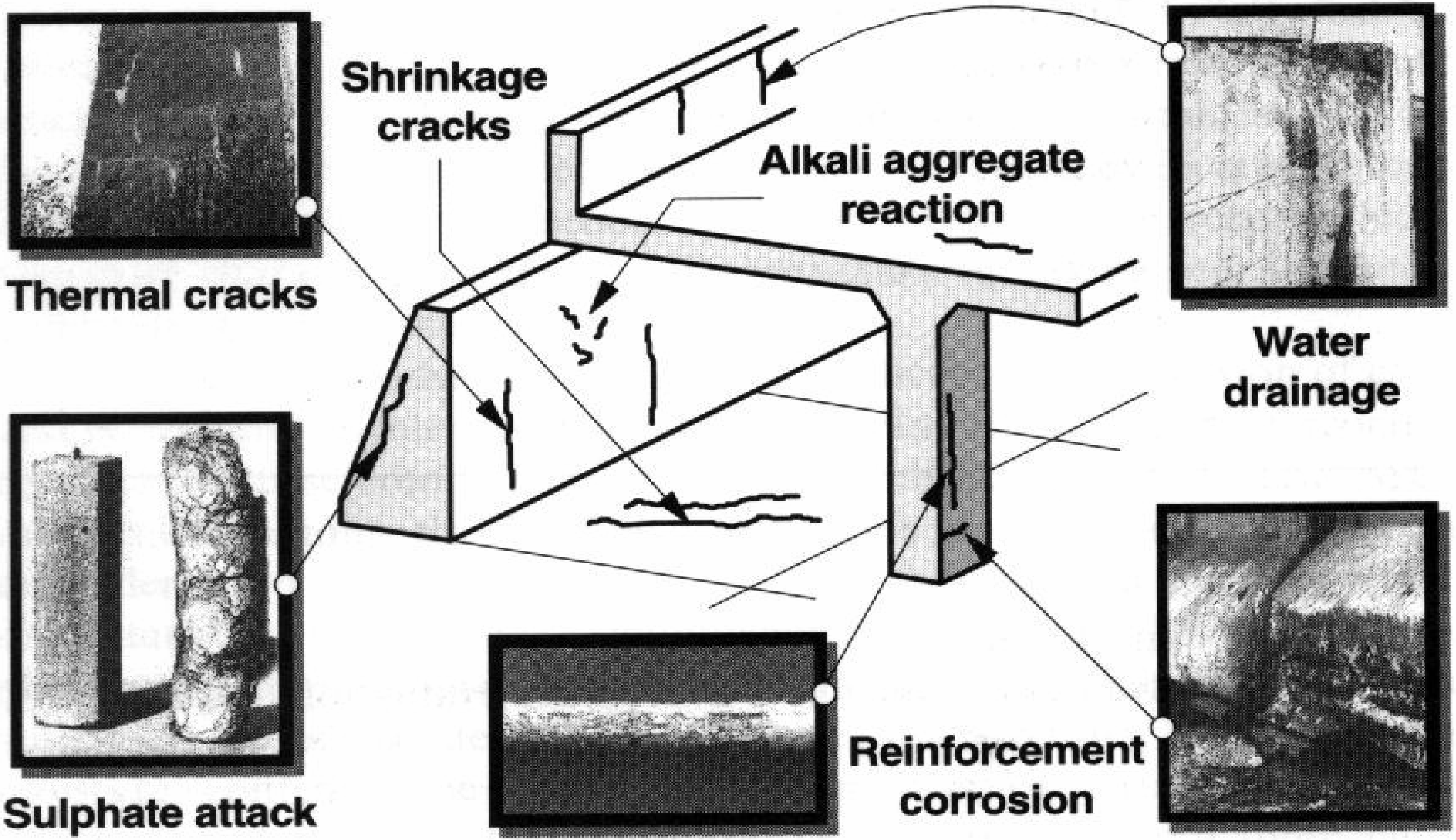
Recently, severe deteriorations in concrete structures, such as bridges, buildings etc., has been criticized in major mass media in Korea : " Korea is Republic of Concrete " .

알아주는 '콘크리트 공화국'이 돼버렸다. 는 것은 사회간접자본(SOC) 투자를 많이 하고 있기 때문만은 아니다. 경 트 발생량이 동시에 늘고 있다는 지적이다. 이었다. 강찬수 기자 envirepo@joongang.co.kr

Japanese daily newspapers warning durability related safety problems of concrete structures

Recently, spalling of concrete from concrete structures, such as bridges, tunnels, etc., has become a big problem criticized in mass media in Japan.

Deterioration in Concrete Structures



Corrosion of PC strands due to poor consolidation

Old and New Durability Concepts

Old Codes: AASHTO, EC2,BS

- Simple deemed-to-satisfy rules (deterministic)
- Experience based rules of thumb
- Poor environmental classification

Result

No relation between performance and service life (implicit 50 years)

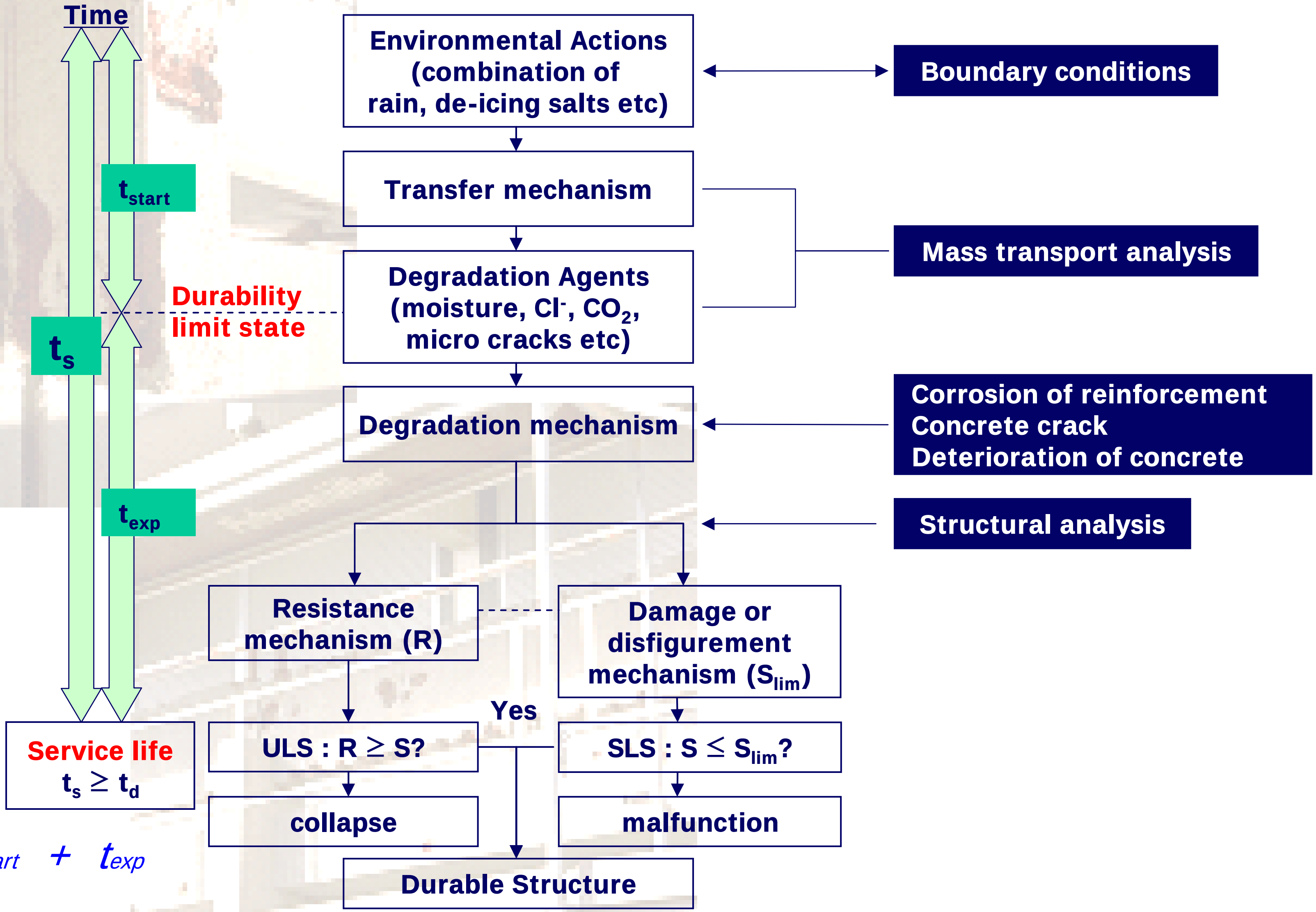
New Codes: Performance-based design

- Degradation models
- Material parameters
- Detailing of environmental actions
- Statistical quantification (mean, standard deviation, distribution)
- Choice of service life

Result

Documented service life design, failure probability

Service Life of RC structures (ISO/WD 13823)



$$t_s = t_{start} + t_{exp}$$

Service life = durability limit + safety limit

ts = tstart + texposure

Durability Analysis

START

Size, shape, mix proportions, initial and boundary conditions

Governing equations

$$\alpha_i \frac{\partial \theta}{\partial t} + divJ_i - Q_i = 0$$

Next iteration

Increment time, continue

Hydration computation
Temperature, Hydration level of Each component

Microstructure computation
Bi-model porosity Distribution, Interlayer porosity

Pore pressure Computation
Pore pressures, RH and moisture distribution

Chloride Transport and equilibrium
Dissolved and Bound chloride concentration

Carbon dioxide Transport and equilibrium
Gas and dissolved CO_2 concentration

Ion equilibrium model
Dissolved Oxygen Transport and equilibrium

Corrosion model
Corrosion rate, Amount of O_2 consumption

Conservation Laws satisfied?

no

yes

at each time step

Serviceability/Safety Analysis

Output

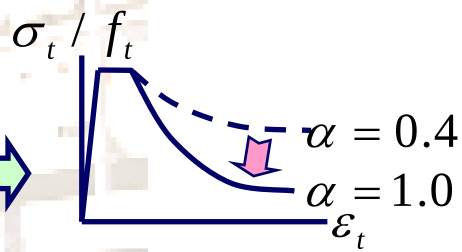
Corrosion rate, crack, tension stiffening factor

Tension stiffening factor : α

Continuum Mechanics
Deformation Compatibility, Momentum Conservation

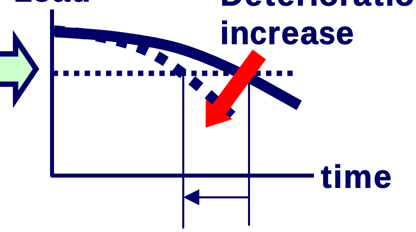
Structural analysis (FEM etc.)

$$\sigma_t = f_t \left(\frac{\varepsilon_{tu}}{\varepsilon_t}\right)^{\alpha}$$



Tension stiffening model

Performance degradation



Concrete Materials, Mechanics & Engineering Lab., Yonsei Univ.

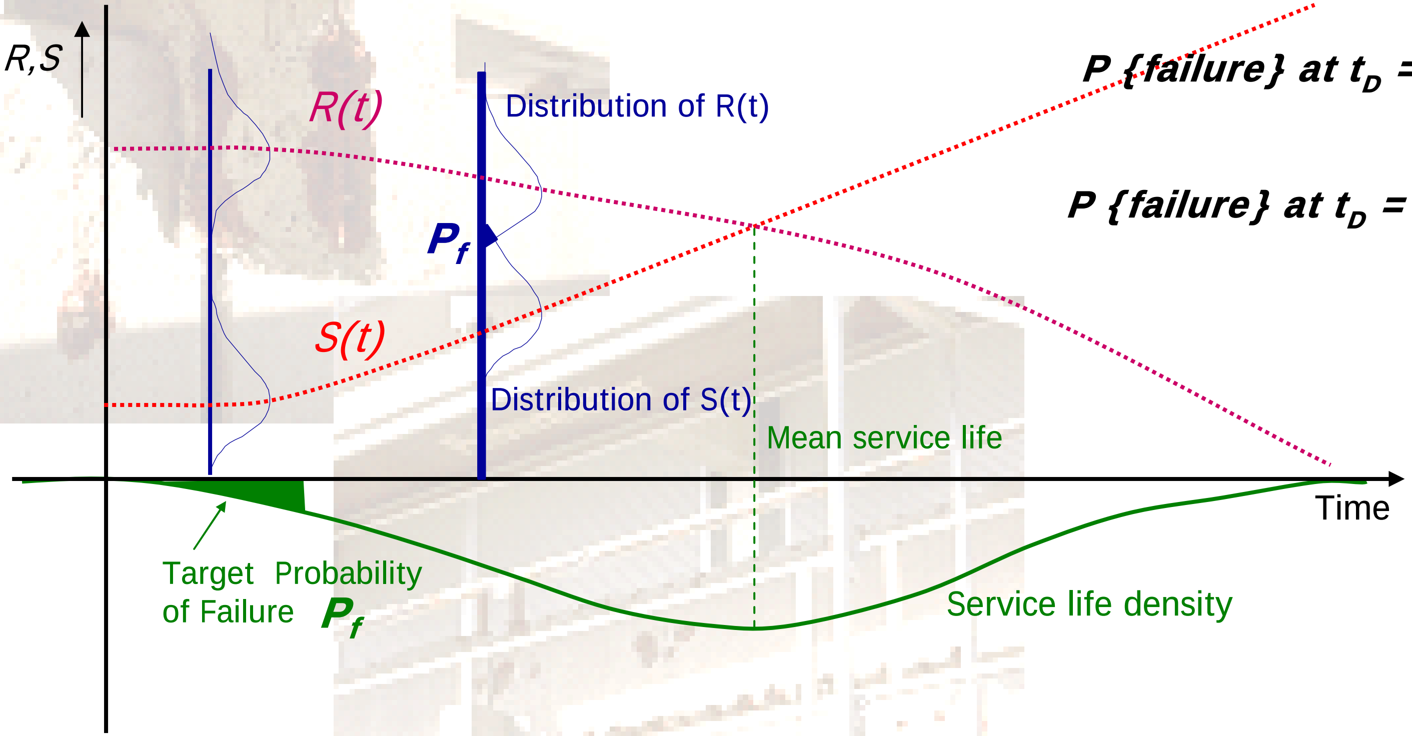
Schematic description of service life design

$t_S = t_{start} + t_{exp}$

t_D : *design service life*

$P\,\{failure\}\text{ at } t_D = P\,\{t_S \leq t_D\} \leq P_{target}$

$P\,\{failure\}\text{ at } t_D = P\,\{R(t_D) \leq S(t_D) < 0\} < P_{target}$



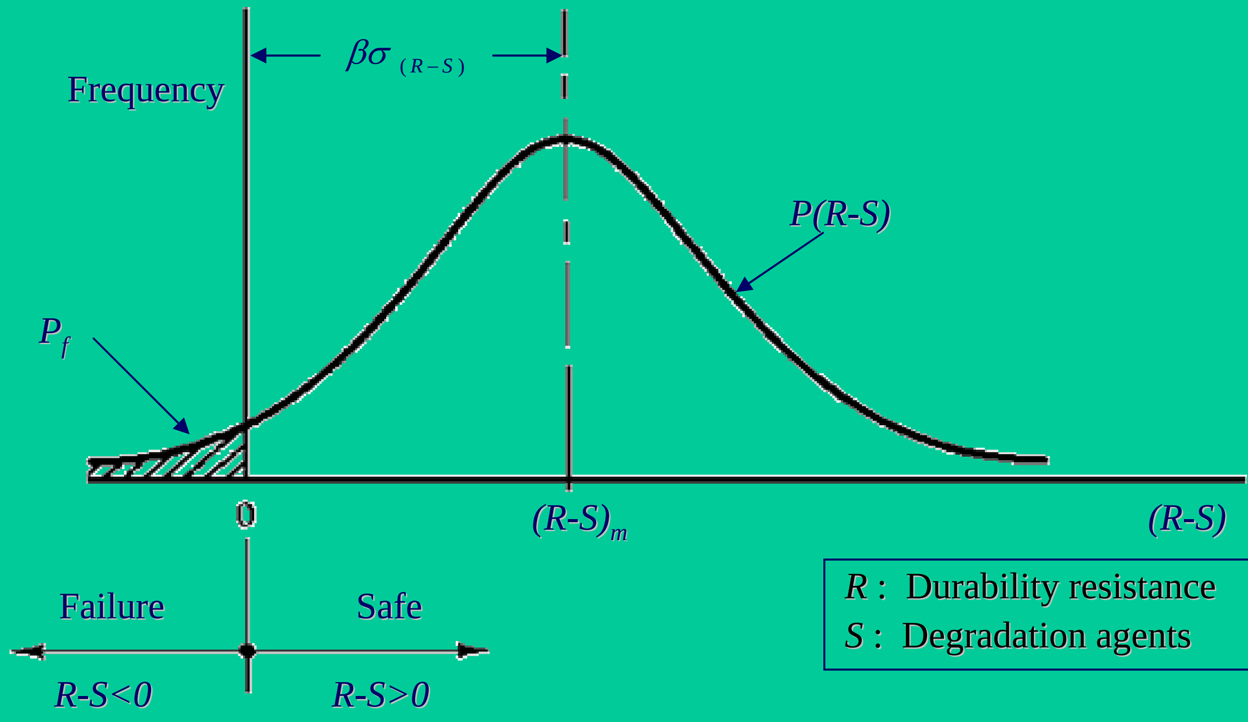
Durability Failure of Concrete Structure

Durability Failure of Structure

$$P_f = P(R - S \leq 0)$$

Reliability Index

$$\beta = \frac{R_m - S_m}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$



R : Durability resistance

S : Degradation agents

Durability Design Strategy

Measures:

- **High quality and impermeable concrete**

  - low chloride diffusivity (material)

  - sufficient concrete cover (design)

  - no early-aged cracks (construction)

→ Performance evaluation tool

↓

verification of 100 years service life

↓

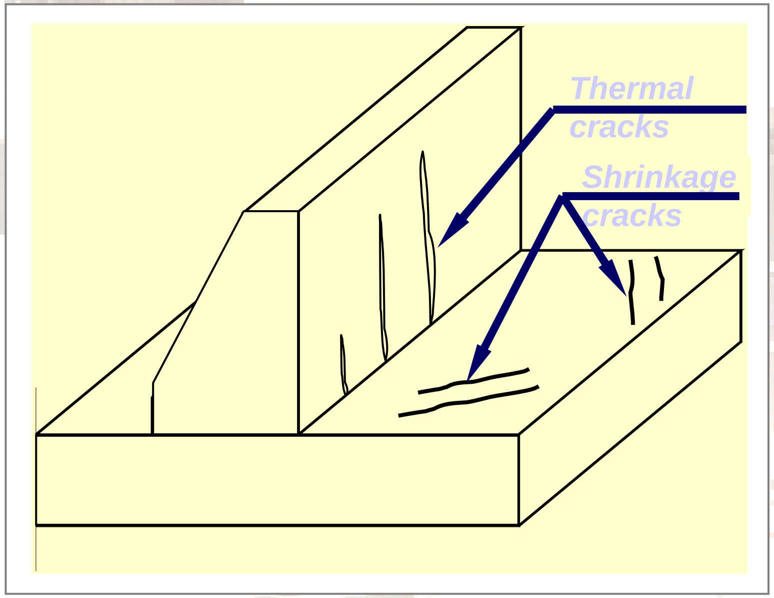
min cover

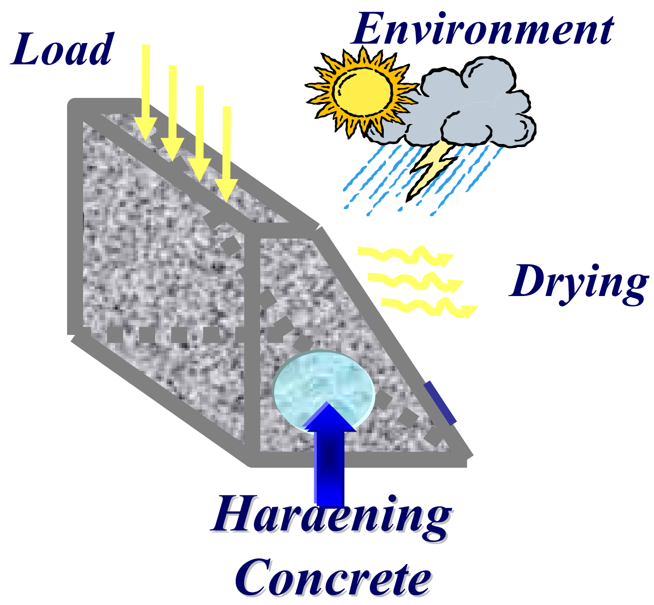
max. D_{cl}

Early-age cracks in concrete limit life span of concrete structures

- Temperature variation properties
- Shrinkage properties
- Strength and stiffness development properties

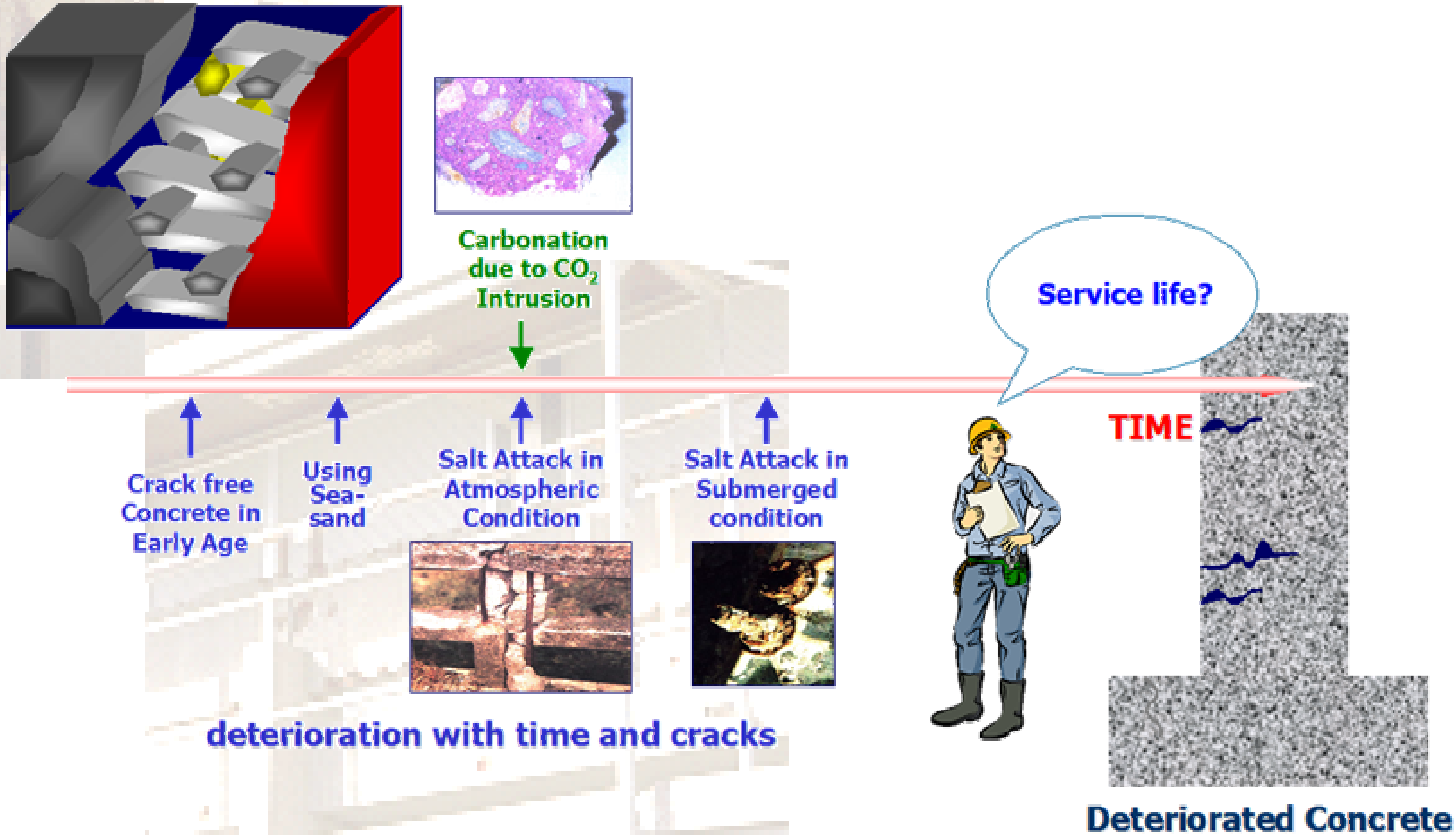
→ **Microcracks** → Degradation of long-term durability performance



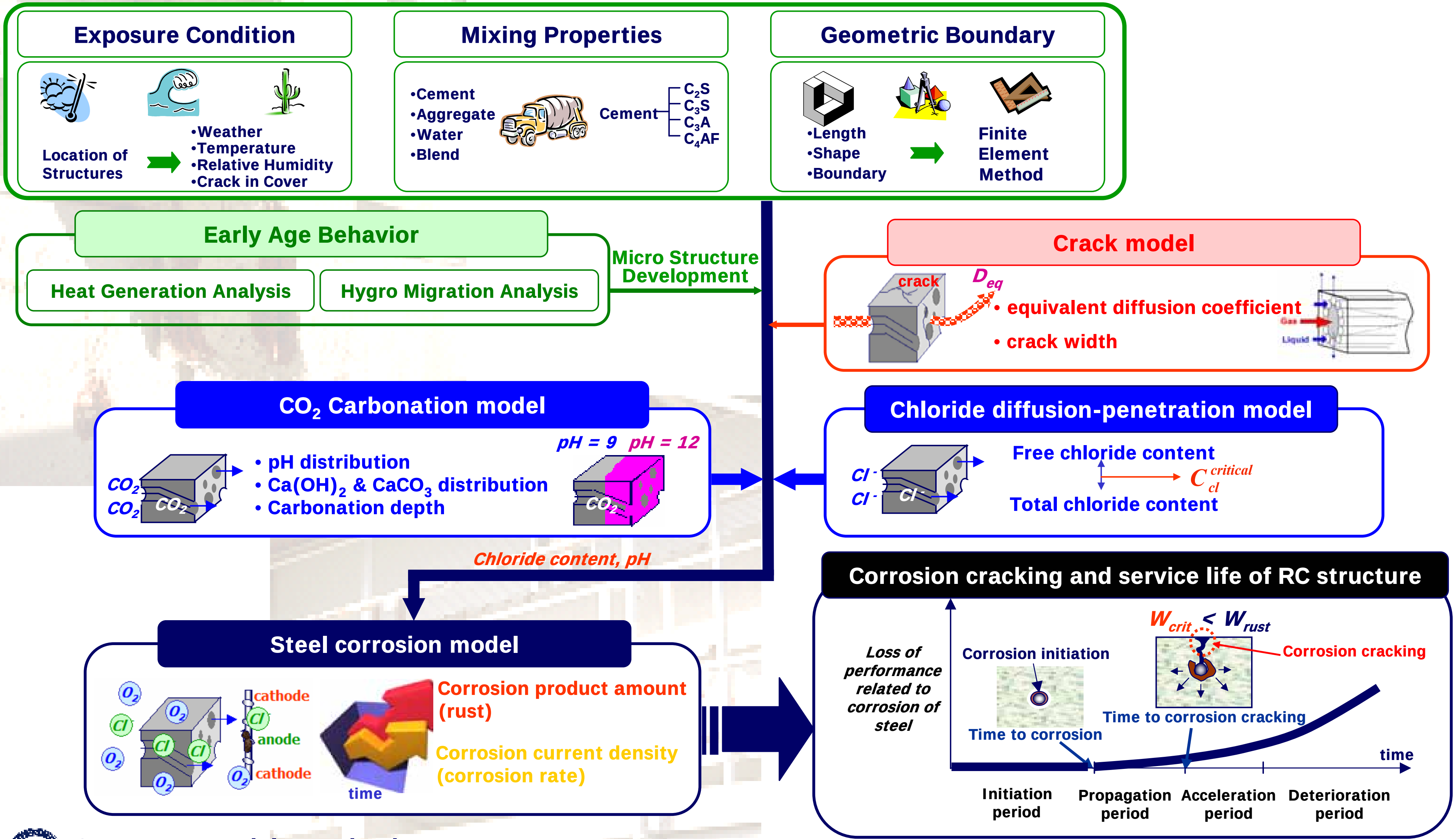


Service Life Prediction on Cracked Concrete

- It is necessary to develop an analytical algorithm of steel corrosion, which considers pre-existing early-age crack and cover concrete quality, for accurate prediction of service life of cracked RC structures subjected to chloride attack or / and carbonation.



Scheme of Service Life Prediction



Concrete Materials, Mechanics & Engineering Lab., Yonsei Univ.

Governing equations for mass and energy conservation for service life prediction

$$\alpha_i \cdot \frac{\partial (X_i)}{\partial t} + divJ_i(X_i, \nabla X_i) - Q(X_i) = 0$$

Variables X_i	Potential term α_i	Flux term J_i	Sink term Q_i
Temperature T	$\rho\ c$ [Kcal/K·m³] - Constant	$-K_H \nabla T$ [Kcal/ m²·s] - Constant	Q_H [Kcal/m³·s] - Multi component heat of hydration model of cement
Pore pressure P	$\phi\rho \frac{\partial S}{\partial P}$ [kg/Pa·m³] - Path dependent moisture isotherms	$-(K_l + K_v)\nabla P$ [kg/ m²·s] - Random geometry of pores and Knudsen vapor diffusion	$-Q_{hyd} - \frac{\partial(\rho S \phi)}{\partial t}$ [kg/ m³·s] - Water combined due to hydration; bulk porosity change effect
Chloride concentration C_{cl}	ϕS [mol.l/mol·m³] - Porosity change dependent	$-D_{cl}^{eq}\nabla C_{cl}$ or $-D_{cl}\nabla C_{cl}$ [mol/ m²·s] - Mass and Knudsen diffusion in sound and/or cracked surface - Temperature and porosity change dependent	Q_{cl} [mol/ m³·s] - Reactive chloride ion content due to binding capacity
CO_2 concentration C_{co_2}	$\phi(1-S)K_{co_2} + \phi S$ [mol.l/mol·m³] - Path dependent transport of mass - Porosity change dependent	$-D_{co_2}^{eq}\nabla C_{co_2}$ or $-D_{co_2}\nabla C_{co_2}$ [mol/ m²·s] - Mass and Knudsen diffusion in sound and/or cracked surface - Temperature and porosity change dependent	Q_{co_2} [mol/ m³·s] - CO_2 consumption due to carbonation process
O_2 concentration C_{o_2}	$\phi(1-S)K_{O_2} + \phi S$ [mol.l/mol·m³] - Path dependent transport of mass - Porosity change dependent	$-D_{o_2}^{eq}\nabla C_{o_2}$ or $-D_{o_2}\nabla C_{o_2}$ [mol/ m²·s] - Mass and Knudsen diffusion in sound and/or cracked surface - Temperature and porosity change dependent	Q_{O_2} [mol/ m³·s] - O_2 consumption due to corrosion process

Equivalent diffusion coefficient for early-age cracks in concrete

❖ *Cracks in REV(Representative Elementary Volume) (Song, 2002)*

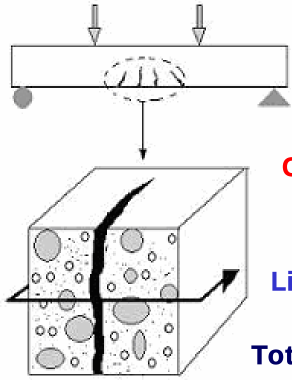
Capillary flux J_{cp} Crack flux J_{cr}

Average method

❑ Flux of chloride ion

❑ Flux of CO_2

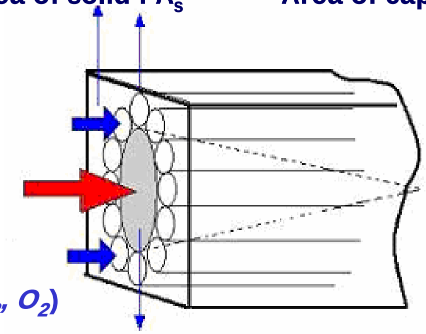
Equivalent diffusivity

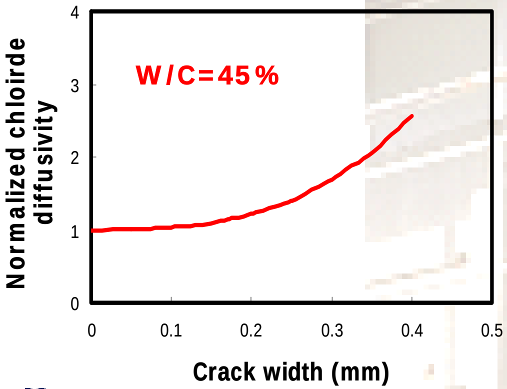


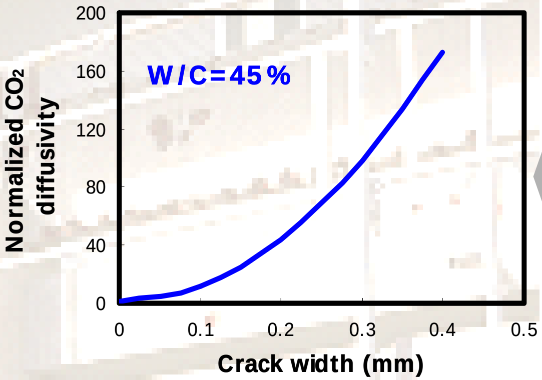
Gas (H_2O, CO_2, O_2)

Liquid (H_2O, cl^-, CO_2, O_2)

Total area : A_o







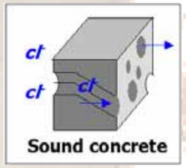
RCPT(Rapidly Chloride Penetration Test)

WPT (Water Permeability Test)

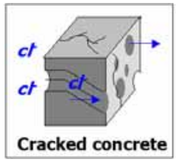
General durability test machine

Chloride diffusion-penetration model

Porosity
Saturation



D_{cl}
D^{eq}_{cl}



Free Chloride Contents

Governing equation of chloride transfer

$$\frac{\partial}{\partial t}(S\phi C_{cl}) + S\phi\left(-D_{cl}\nabla\frac{C_{cl}}{\Omega} + q_s C_{cl}\right) - Q_{cl} = 0$$

Early-age behavior

Pore structure formation

Potential term — Flux term — Sink term

pore structures, moisture transport
diffusion & permeability coefficient with crack

Flux term

$$\left(\theta + C_{cl}^{A-1}\frac{A10^B(1-\phi)}{1000}\frac{W_{conc}}{M_{cl}}\right)\frac{\partial C_{cl}}{\partial t} = -div(J_{cl})$$

$$J_{cl} = -\left\{\frac{\Omega C_{cl}}{8\mu A_0}\left(\frac{\phi}{\Omega}\int_0^{r_c} r^2 dV + \frac{\pi r^4{}_{crack}}{3}\right)\frac{\partial P}{\partial x} + \left(\frac{\Omega D_{crack}}{R_a} + \theta D_{cl}\right)\frac{\partial C_{cl}}{\partial x}\right\}$$

Equivalent diffusion coefficient of cl^-

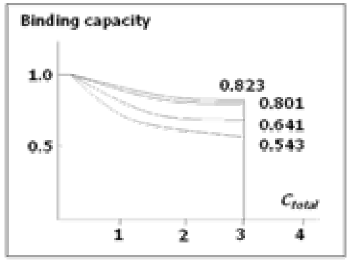
$$D_{cl}^{eq} = \left(\frac{\Omega D_{crack}}{R_a\theta} + D_{cl}\right)$$

permeability coefficient

$$k = \frac{\Omega}{8A_0\theta}\left(\frac{\phi}{\Omega}\int_0^{r_c} r^2 dV + \frac{\pi r^4{}_{crack}}{3}\right)$$

Sink term

Sink term modeling (Tang, 1996)



Binder	$C_t < 0.1$ / $0.1 < C_t \le 3.0$ / $C_t > 3.0$	$\alpha_{fix} = 1.0$ / $1-[A\cdot(C_t-0.1)]^{0.25}$ / B
	A	B
OPC	1	0.543
SLAG30+OPC70	1	0.641
F30+OPC70	1	0.801
S50+OPC50	1	0.823

$$C^n_{bound} = C^n_{free}\cdot\left(\frac{1}{\alpha_{fixed}} - 1\right)^{-1}$$

Reactive chloride ion contents in materials

$$Q_{cl} = -\frac{C^{n+1}_{bound} - C^n_{bound}}{t_{n+1} - t_n}\cdot\frac{W_{pow}}{M_{cl}}\cdot 10^{-2}$$

Sink term in coupled deterioration analysis

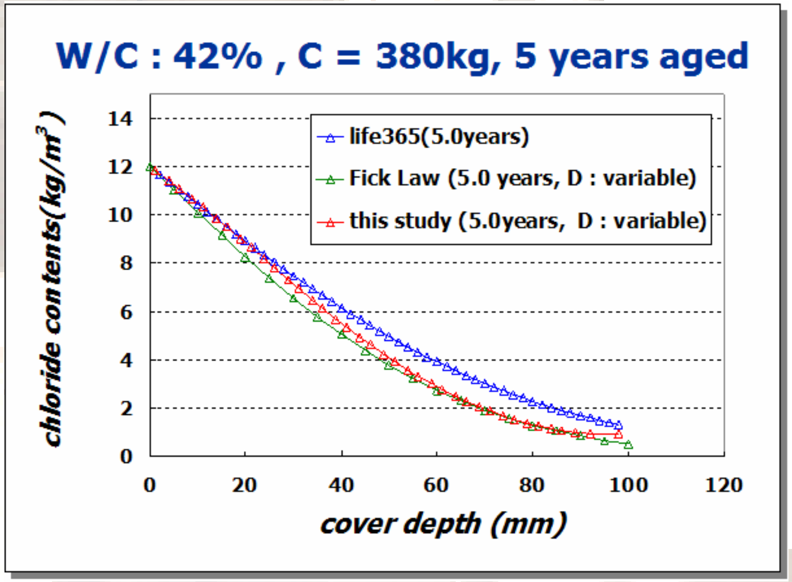
$$Q_{cl} = -\frac{C^{n+1}_{bound} - C^n_{bound}}{t_{n+1} - t_n}\cdot W_{pow}\times 10^{-2} - Q^{cb}_{cl}$$

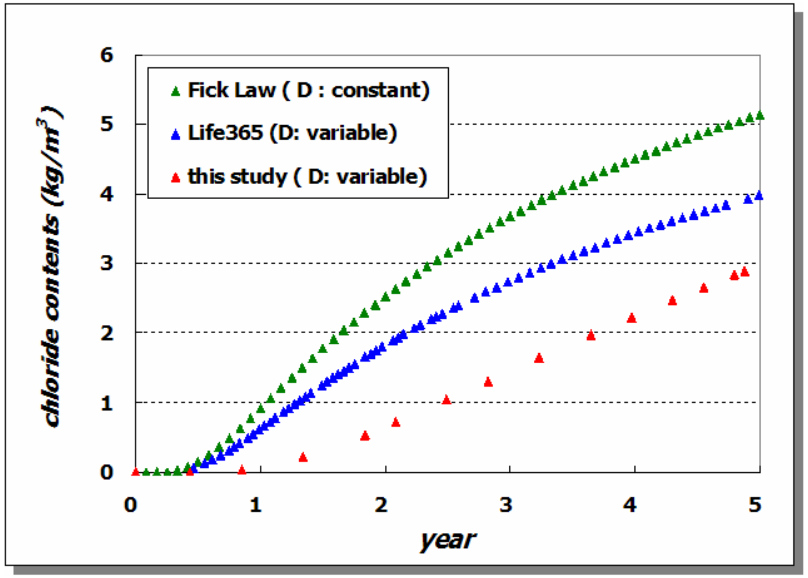
Decreasing of binding capacity

Where, $Q^{cb}_{cl} = -\frac{C^{n+1}_{bound} - C^n_{bound}}{t_{n+1} - t_n}\cdot W_{used}\times 10^{-2}$

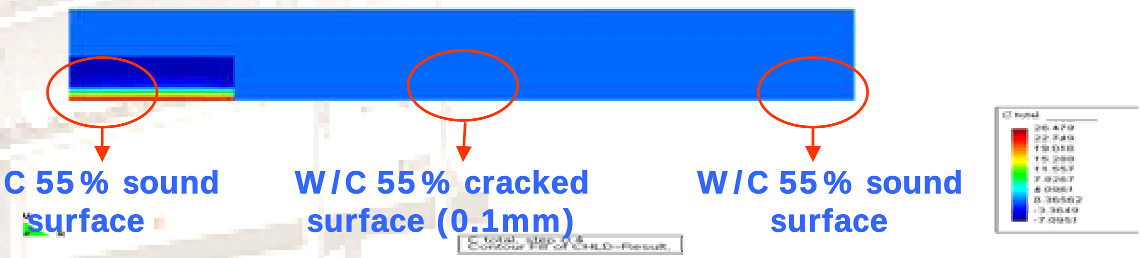
W_{used} : consumption of cement components at carbonated area

Analysis results for chloride attack

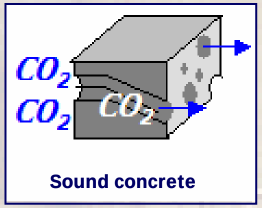




Beam Analysis (H:6cm, L: 28cm)

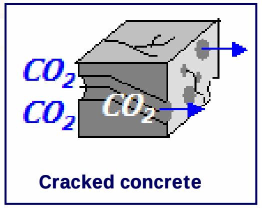


CO_2 carbonation model



Porosity
Saturation

D_{co2}
D^{eq}_{co2}

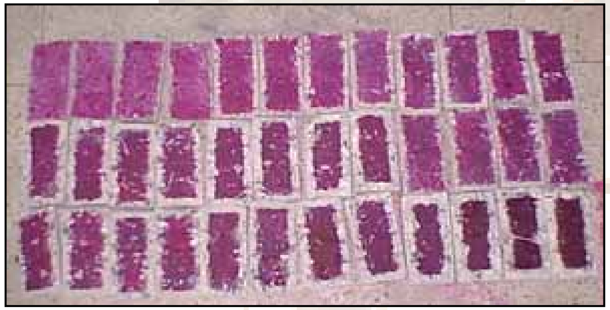


Carbonation depth, $Ca(OH)_2$ & $CaOH_3$, pH distribution

Governing equation of CO_2 transfer

$$\frac{\partial}{\partial t}\{\phi[(1-S)\cdot\rho_g + S\cdot\rho_d]\} + div\ J_{co_2} - Q_{co_2} = 0$$

Potential term — Flux term — Sink term



■ Healthy area □ Carbonation area

Potential term

Density of CO_2 : $\rho_{gco_2} = \frac{M_{co_2}}{RT}\cdot H_{co_2}\cdot\rho_{dco_2} = K_{co_2}\cdot\rho_{dco_2}$

$$K_{co_2} = \frac{M_{co_2}}{RT}H_{co_2} = \frac{1}{RT\cdot n_{H_2O}}$$

Ideal gas equation

Henry constant $H'_{co_2} = H_{co_2}\cdot n_{H_2O}\cdot M_{co_2}$

Flux term

- Diffusion coefficient of gaseous CO_2 in pores : $D_{gco_2} = \frac{\phi\cdot D^g_{co_2}}{\Omega}\frac{(1-S)^4}{1+l_m/2(r_m-t_m)}$
- Diffusion coefficient of dissolved CO_2 in pores : $D_{dco_2} = \frac{\phi\cdot S^4}{\Omega}D^d_{co_2}$
- Equivalent diffusion coefficient of CO_2 in cracked concrete :

$$D^{eq}_{co_2} = D_{sound} + D_{crack}\cdot\Omega\frac{K_{co_2}}{R_a\theta}$$

CO_2 flux

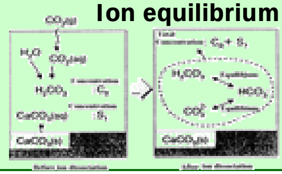
$$J_{co_2} = -(D_{gco_2}\cdot K_{co_2} + D_{dco_2})\nabla\rho_{dco_2}$$

Molecular diffusion theorem
Knudsen diffusion theorem

Sink term

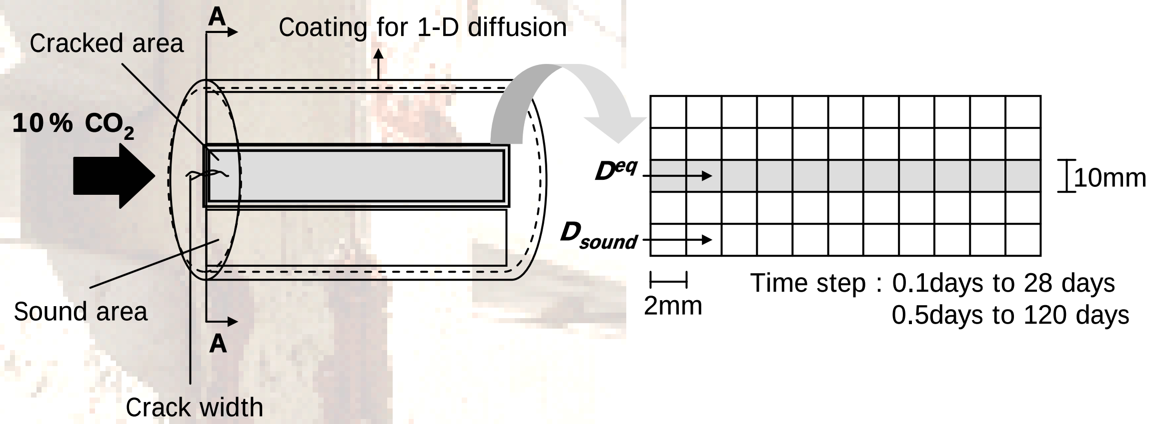
$$Q_{co_2} = \frac{\partial(C_{CaCO_3})}{\partial t} = k[Ca^{2+}][CO_3^{2-}]$$

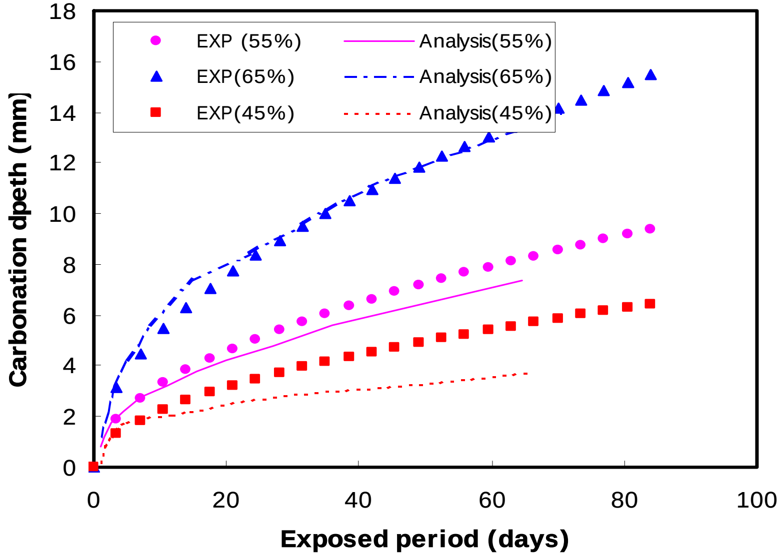
Ion equilibrium



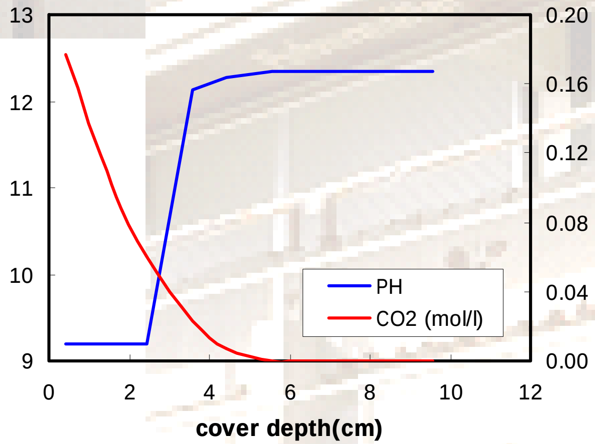
$$H_2O \leftrightarrow H^+ + OH^-$$
$$Ca(OH)_2 \leftrightarrow Ca^{2+} + 2OH^-$$
$$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$$
$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$$

Analysis results for carbonation

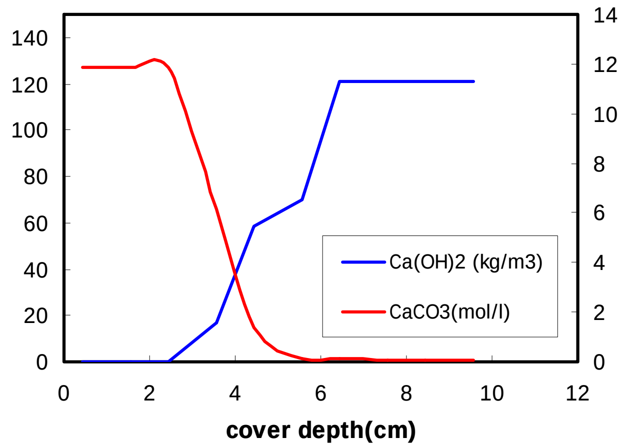




❖ **W/C 55% , CO_2 10%, 1800days after**

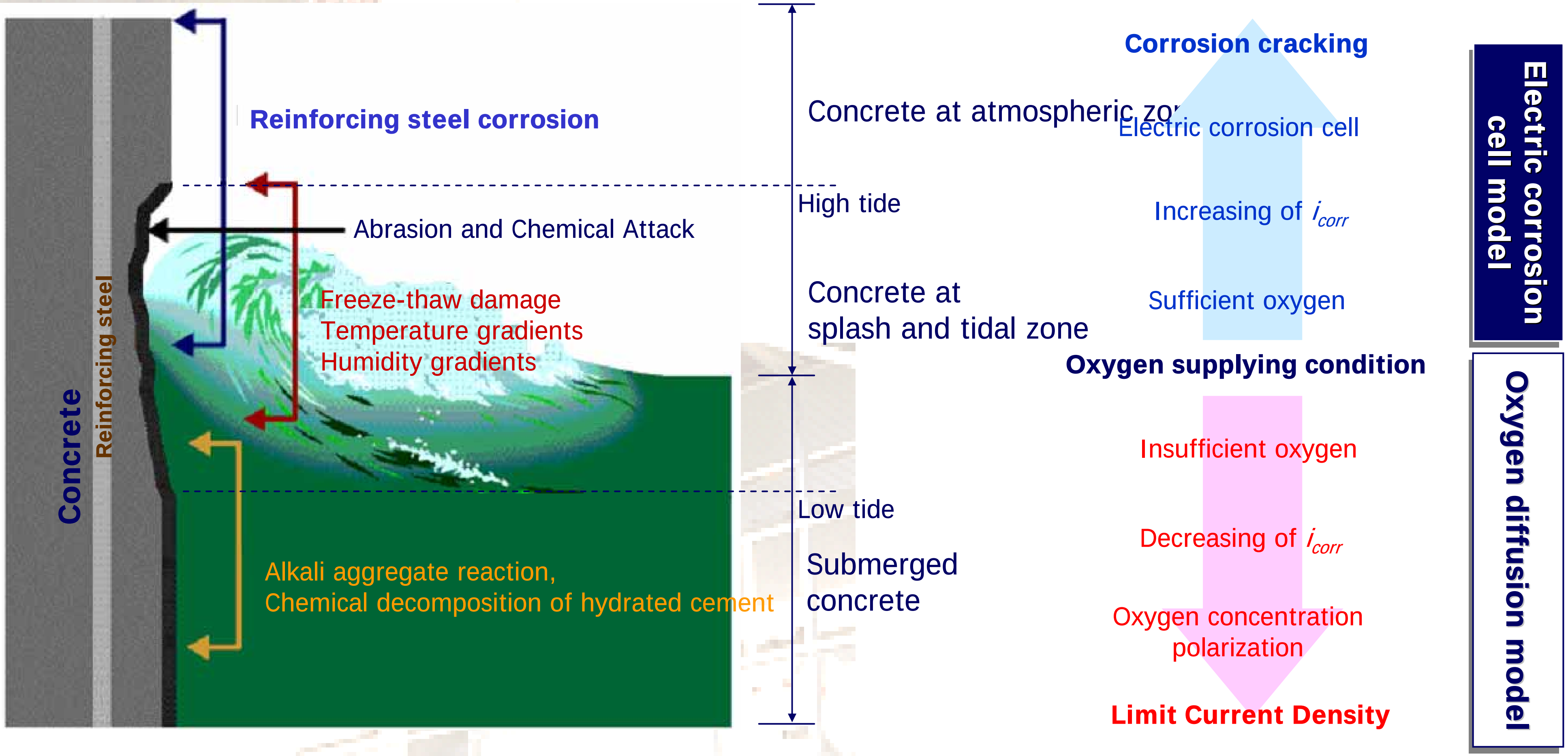


(a) pH and CO_2 concentration distribution



(b) $Ca(OH)_2$ and $CaCO_3$ distribution

Steel corrosion model



Computational flow of steel corrosion model

Moisture transport

Hydration heat analysis

- Micro structure
- Pore pressure
- Pore saturation

❑ Early-age behavior analysis

❑ Salt attack analysis

❑ Carbonation analysis

- Free chloride content
- pH in concrete
- Porosity and saturation

Corrosion Analysis Models

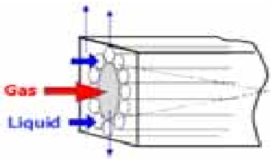
Electric corrosion cell Model	Oxygen diffusion Model
▪ Tafel method analysis	▪ Formulation of O_2 diffusion
(Splash zone)	(Submerged zone)

Prediction of life time in RC structures

Consideration of early age cracks for steel corrosion model

Crack Effect

Chloride Ion Penetration Analysis

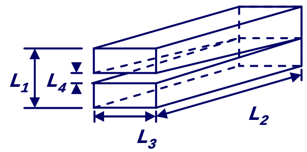


Equivalent Diffusion Coefficient

$$D_{cl}^{eq} = \left(\frac{\Omega D_{crack}}{R_a^0} + D_{cl}\right)$$

$$\frac{D_{crack}}{D_{cl}} = 2099\, w^2 + 96\, w$$

Oxygen Diffusion Analysis



Equivalent Diffusion Coefficient

$$D_{crack} = D_O^d$$

$$D_{eq} = \frac{1}{L_4}[\{(L_1 - 0.5L_4)(D_{gO_2}K_{O_2} + D_{dO_2})\} + 0.5L_4 D_O^d$$

Corrosion Analysis Algorithm

Chloride Thresholds

Free Chloride Contents

Exposure Conditions

Flux of Dissolved O_2

Splash Zone

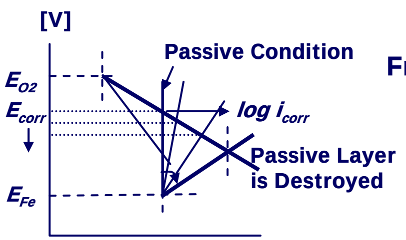
Submersed Structure

O_2 : Sufficient

O_2 : Sufficient

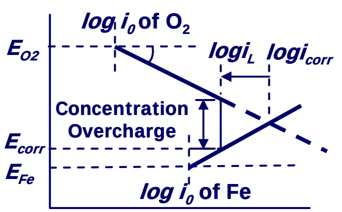
O_2 : Insufficient

Electric corrosion cell model



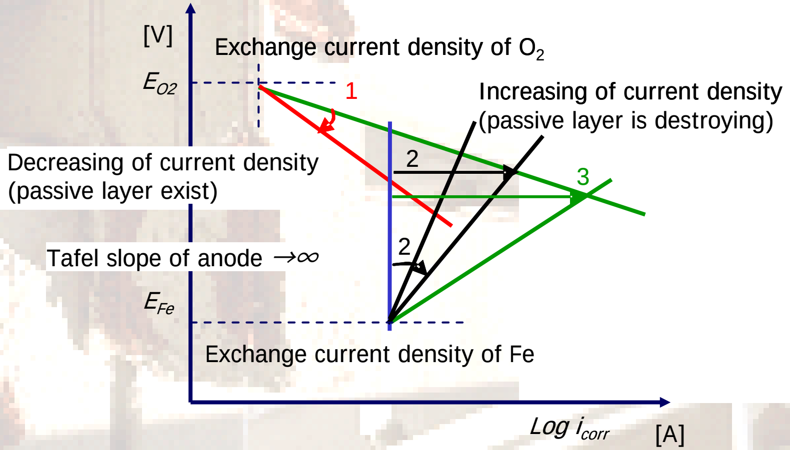
Free Chloride Contents
↓
Changing Anode Tafel Slope
↓
Increasing Corrosion Current Density

Oxygen diffusion model



Consumption Dissolved O_2
↓
O_2 Supply is Insufficient
↓
Generation of Concentration Slope
↓
i_{corr} is Limit Current Density

Electric corrosion cell model



Corrosion Potential

SHE+ Activation Overcharge

(Standard Hydrogen Electrode)

Anode : $E_{corr} = E_{Fe} + \eta^{a}$

Cathode : $E_{corr} = E_{O_2} + \eta^{c}$

Corrosion Current Density : $i_{corr} = i_a = i_c$

Chloride Thresholds

Condition of Steel: *Passive* | *Passive Layer is Destroying* | *No Passive Layer*

Total Chloride Thresholds

1.2 kg/m³ (KCI, JCI specification)

2.4 kg/m³ (Hausmann, 1969)

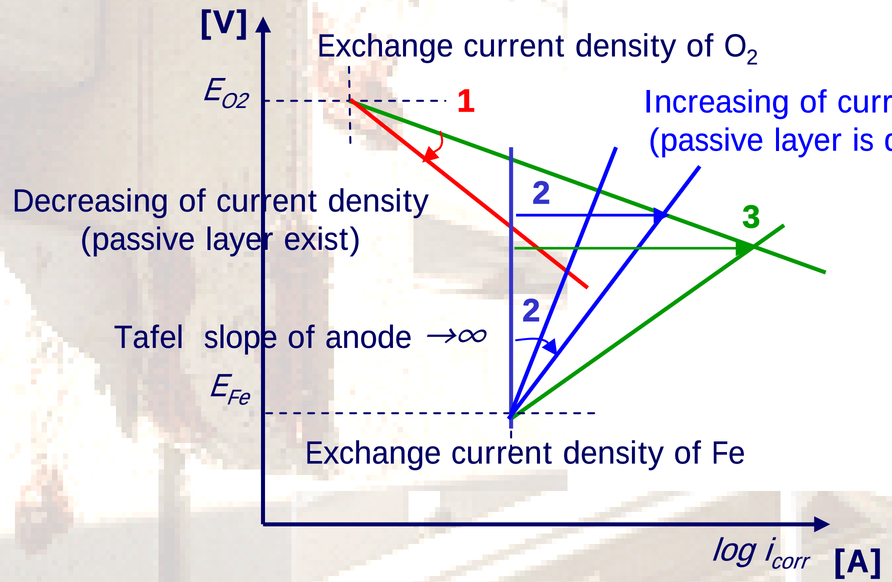
↓

Free Chloride Thresholds

Corrosion Start → $[cl^{-}]_i = \frac{1.2}{cement\ \ weight}(1-\alpha_{fixed})$

No Passive Layers → $[cl^{-}]_e = \frac{2.4}{cement\ \ weight}(1-\alpha_{fixed})$

Corrosion stage vs corrosion current density



Stage 1

- Passive Condition
- $Cl^- < 1.2$ kg/m^3
- Anode Tafel Slope = ∞
- Cathode Tafel Slope = 2β

Stage 2

- Passive Layer is Destroying
- 1.2 kg/m^3 (KCl) < Cl^- < 2.4 kg/m^3
- Anode Tafel Slope

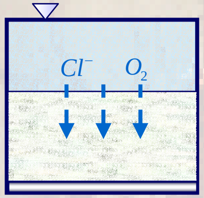
$$\beta = \frac{0.059\left([cl^-]_e - [cl^-]_i\right)}{[cl^-] - [cl^-]_i}$$

Stage 3

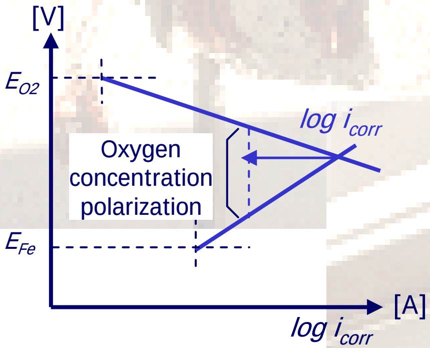
- No Passive Layer
- Cl^- = 2.4 kg/m^3 (Hausmann, 1969)
- Not increase i_{corr}

Condition of the passive layers	Corrosion current density (A/m²)
Exist	$\log i_{corr} = \log i_{O_{Fe}}$
Being destroyed	$\log i_{corr} = \dfrac{0.998 - 0.06pH - 0.059\log i_{O_2} + \beta \log i_{O_{Fe}}}{\beta + 0.059}$ $\beta = \dfrac{0.059\left([cl^-]_e - [cl^-]_i\right)}{[cl^-] - [cl^-]_i}$ [cl^-] : free chloride content(% wt of cement) at the stage [cl^-]$_i$: free chloride content(% wt of cement) for the stage of corrosion initiation [cl^-]$_e$: free chloride content(% wt of cement) for the stage of no passive layers
No exist	$\log i_{corr} = 8.458 - 0.508pH + 0.5\log i_{O_2} + 0.5\log i_{O_{Fe}}$

Consideration of early age cracks for oxygen diffusion model



Submerged structures



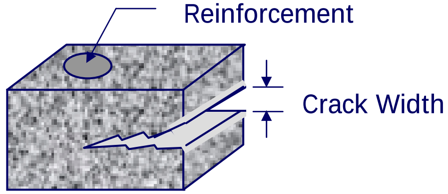
Oxygen diffusion control

$$\frac{\partial}{\partial t}\{\phi[(1-S)\cdot\rho_{gO_2}+S\cdot\rho_{dO_2}]\}+div(J_{O_2})-Q_{O_2}=0$$

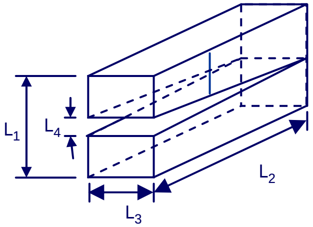
Capacity | Flux | Sink

- $\rho_{gO_2} = \frac{M_{O_2}}{RT}\cdot H_{O_2}\cdot\rho_{dO_2} = K_{O_2}\cdot\rho_{dO_2}$
- $J_{O_2} = -(D_{gO_2}\cdot K_{O_2} + D_{dO_2})\nabla\rho_{dO_2}$
- $Q_{O_2} = -\phi S\frac{M_{O_2} i_{corr}}{z_{O_2}F}\cdot\frac{A_{bar}}{V_{elem}}$

D_{eq}



Modified 1-D Anisotropic Crack Model



Equivalent Oxygen Diffusion Coefficient

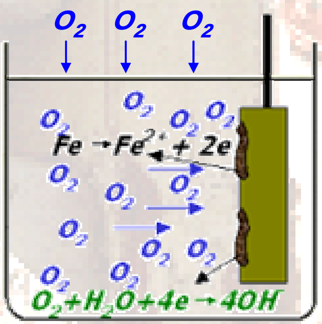
$$D_{gO_2} = \frac{\phi D^g_{O_2}}{\Omega}\frac{(1-S)^4}{1+l_m/2(r_m-t_m)}$$

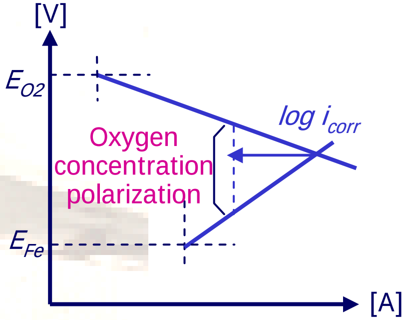
$$D_{dO_2} = \frac{\phi S}{\Omega}D^d_{O_2}$$

$$D_{crack} = D^d_{O_2}$$

$$D^{eq}_{O_2} = \frac{1}{L_4}[\{(L_1-0.5L_4)(D_{gO_2}K_{O_2}+D_{dO_2})\}+0.5L_4D^d_{O_2}$$

Oxygen Diffusion Model





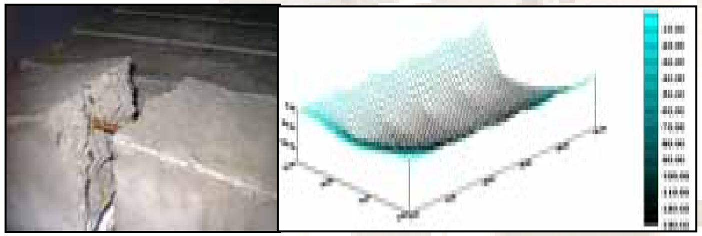
Oxygen diffusion control

Ishida(1999)

Governing equation of oxygen diffusion

$$\frac{\partial}{\partial t}\left\{\phi\left[(1-S)\cdot\rho_{gO_2}+S\cdot\rho_{dO_2}\right]\right\}+div(J_{O_2})-Q_{O_2}=0$$

Potential term — Flux term — Sink term



Potential term

Density of O_2 : $\rho_{go_2} = \frac{M_{o_2}}{RT}\cdot H_{o_2}\cdot\rho_{do_2} = K_{o_2}\cdot\rho_{do_2}$ ← Ideal gas equation

$$K_{o_2} = \frac{M_{o_2} H'_{o_2}}{RT} = \frac{1}{RT\cdot n_{H_2O}}$$

Henry constant: $H'_{o_2} = H_{o_2}\cdot n_{H_2O}\cdot M_{o_2}$

Flux term

Diffusion coefficient of gaseous O_2 in pores : $D_{go_2} = \frac{\phi\cdot D^g_{o_2}}{\Omega}\frac{(1-S)^4}{1+l_m/2(r_m-t_m)}$

Diffusion coefficient of dissolved O_2 in pores : $D_{do_2} = \frac{\phi\cdot S^4}{\Omega}D^d_{o_2}$

Equivalent coefficient of O_2 in cracked concrete

O_2 flux

$$J^{total}_{O_2} = -\frac{1}{L_1}\left[\{(L_1-0.5L_4)(D_{gO_2}K_{O_2}+D_{dO_2})\}+0.5L_4D^d_O\right]\nabla\rho_{dO_2}$$

Molecular diffusion theorem

Knudsen diffusion theorem

Sink term

The rate of O_2 consumption

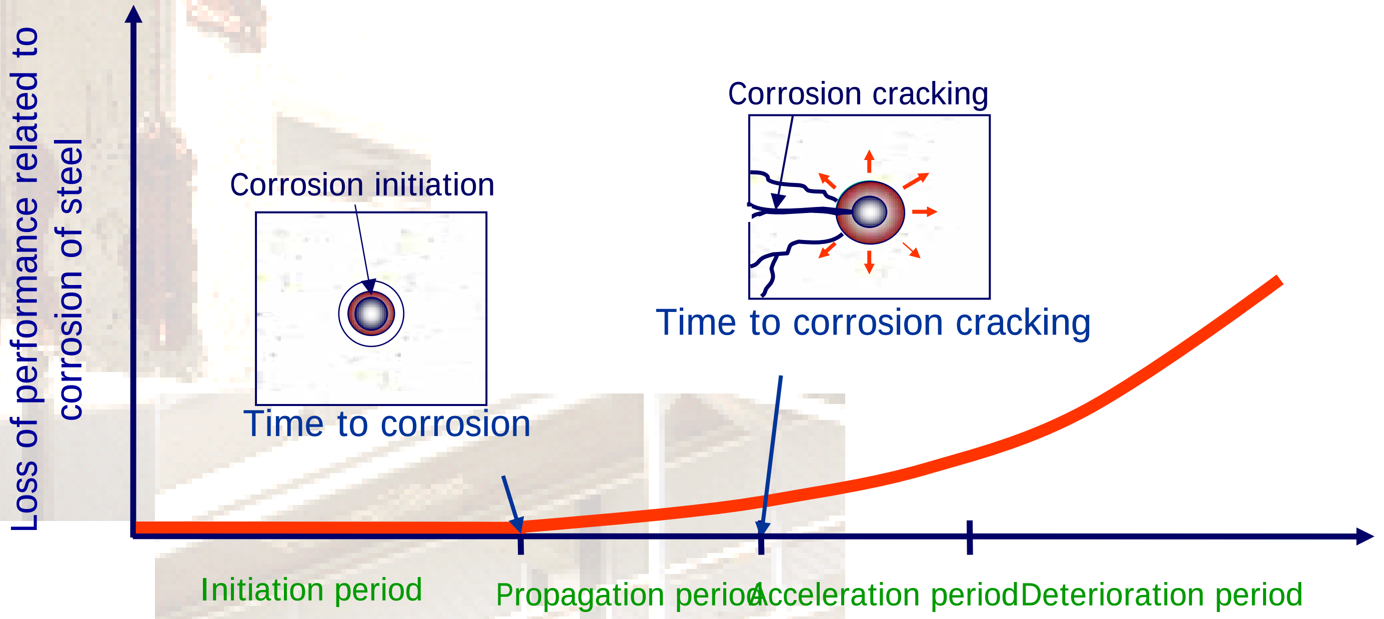
$$Q_{O_2} = -\phi S\frac{M_{O_2}i_{corr}}{z_{O_2}F}\cdot\frac{A_{bar}}{V_{elem}}$$

Faraday's law

Corrosion rate in concrete

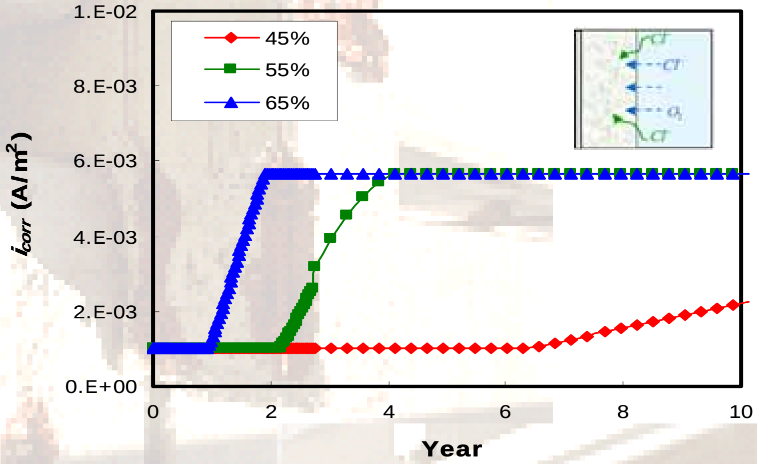
$$R_{corr} = \phi S\frac{M_{Fe}\cdot i_{corr}}{z_{Fe}F}$$

Loss of performance due to steel corrosion

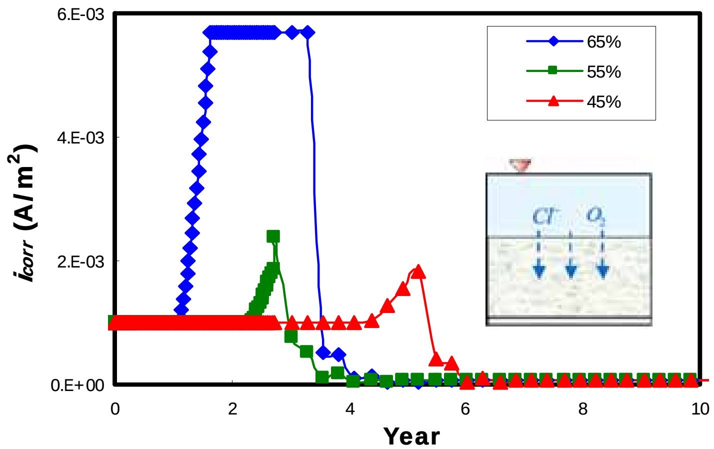


Analysis results for steel corrosion tendency

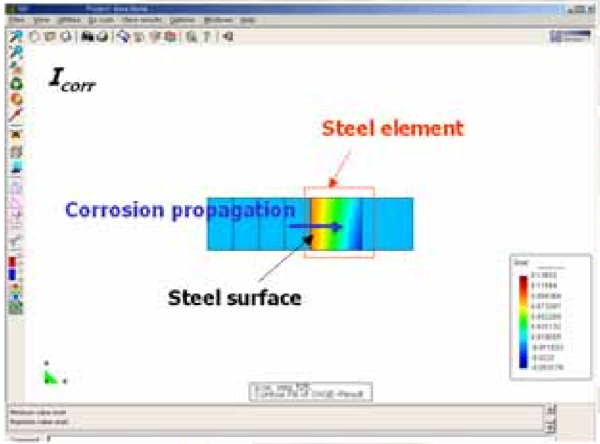
❑ Splash zone structure

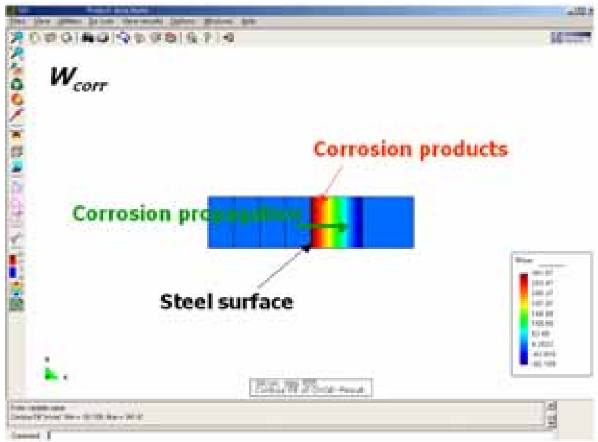


❑ Submerged zone structure



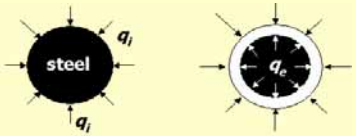
❑ Visualization of steel analysis





Corrosion cracking model

Deformation of steel

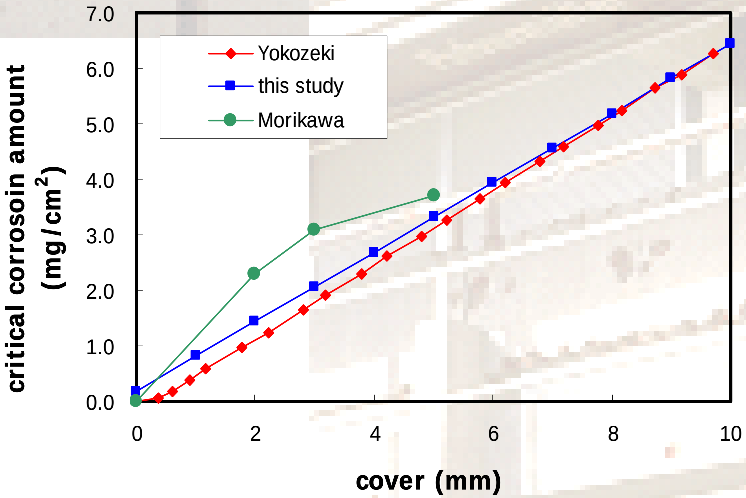


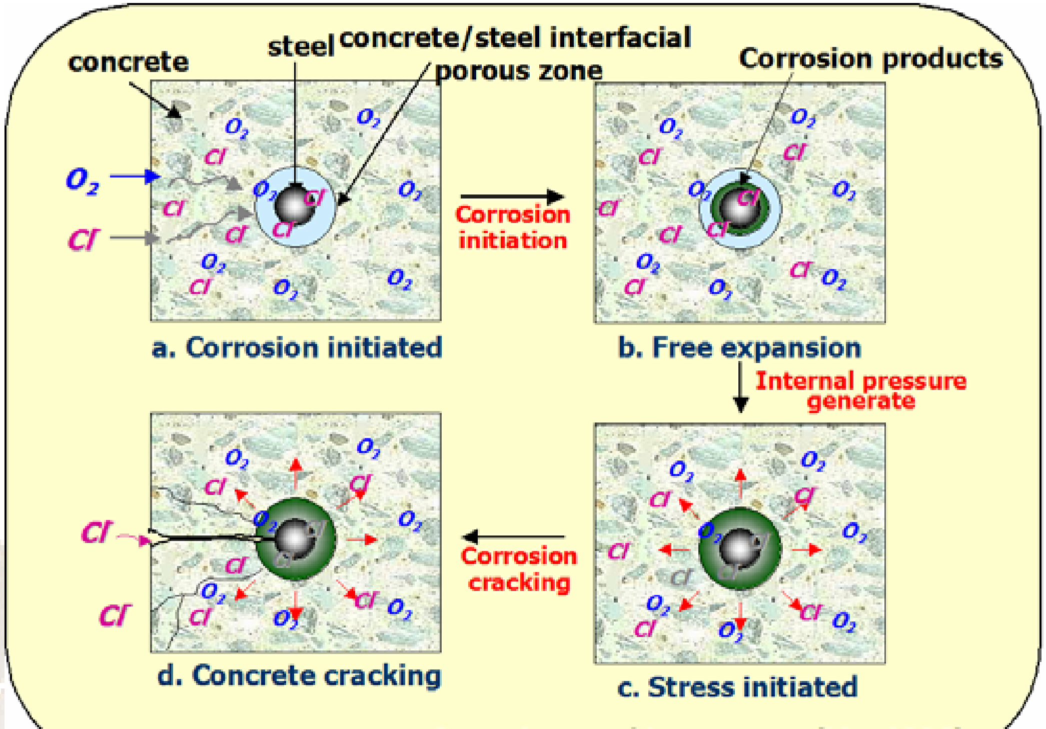
Thickness of corrosion product induced corrosion cracking

$$d_s = B\{2\alpha_p(1-\nu_r) - K^2(1-2\nu_r) - 1\}q_e$$

Critical corrosion amounts

$$W_{crit} = \pi D \frac{\rho_{st}\rho_{rust}}{\rho_{st} - \kappa\rho_{st}}\{[d_0 + d_s]\}$$



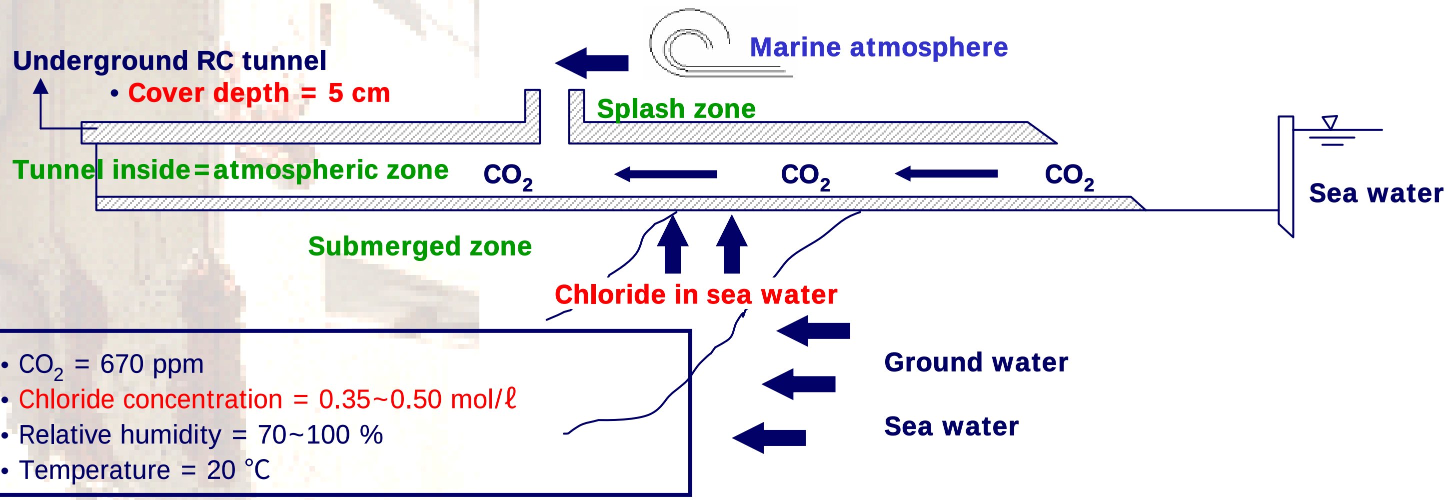


Corrosion cracking process (Liu, 1996)

	Critical corrosion amount (mg/cm^2)		
cover (cm)	2	3	5
Yokozeki (1997)	1.1	1.8	3.1
Morikawa (1987)	2.3	3.1	3.7
This study	1.4	2.0	3.2

f_{ck} = 320 kgf/cm^2, steel diameter : 16mm

Example for service life prediction of RC which does not considered the concept of service life



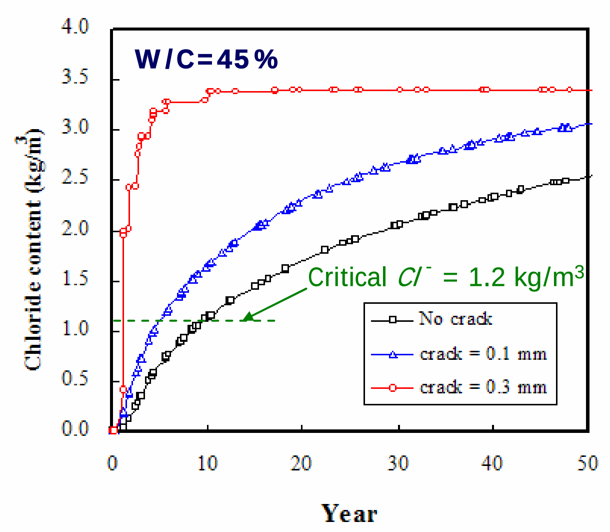
❖ *Mix proportions*

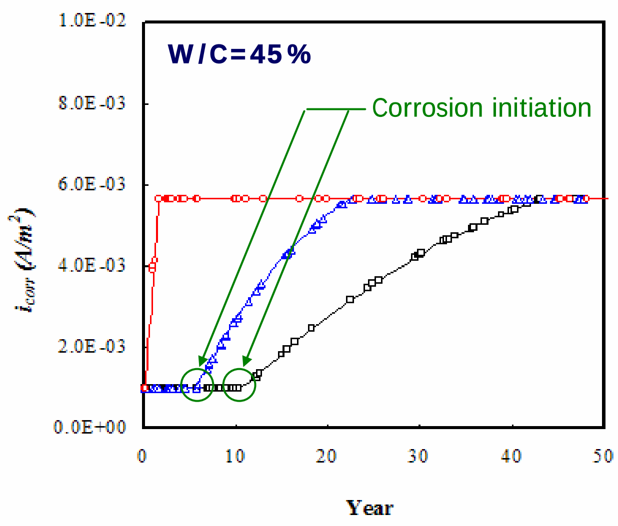
Water/Cement Ratio (%)		45	55
Ordinary Portland Cement (kg/m³)		365	291
Cement Composition	C_3A	10.4	10.4
	C_3S	47.2	47.2
	C_4AF	9.4	9.4
	C_2S	27	27
	Mono Sulfate	3.9	3.9
Coarse Aggregate (kg/m³)		1102	1078
Sand Aggregate (kg/m³)		735	812

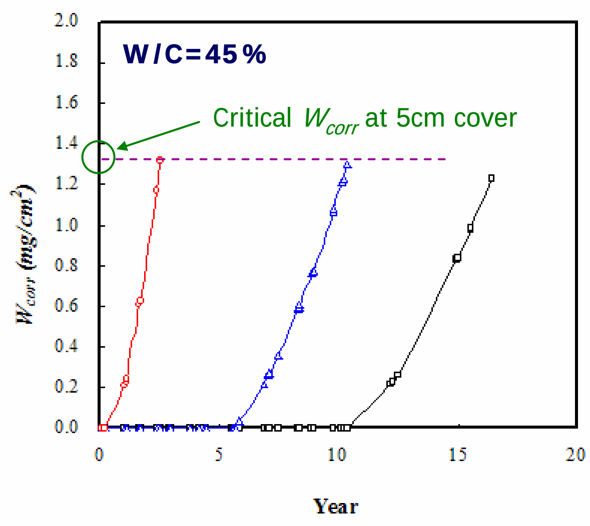
❖ *Environmental conditions*

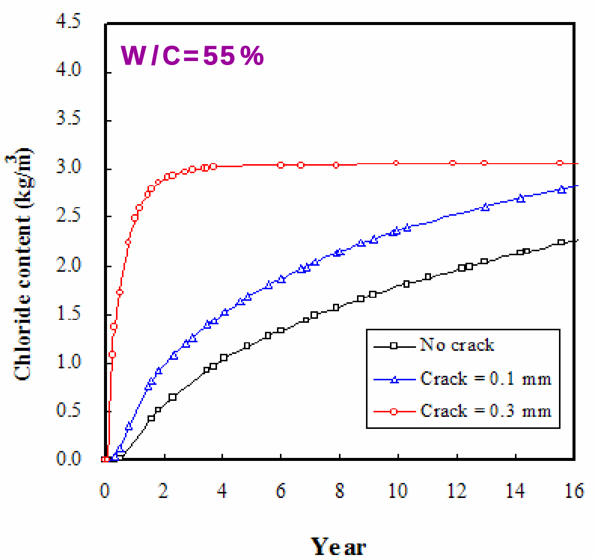
W/C	pH	External chloride concentration (mol/L)	Relative humidity (%)	Temperature
45, 55	9~11	0.35	70	20
45, 55	10~11	0.5	100	20

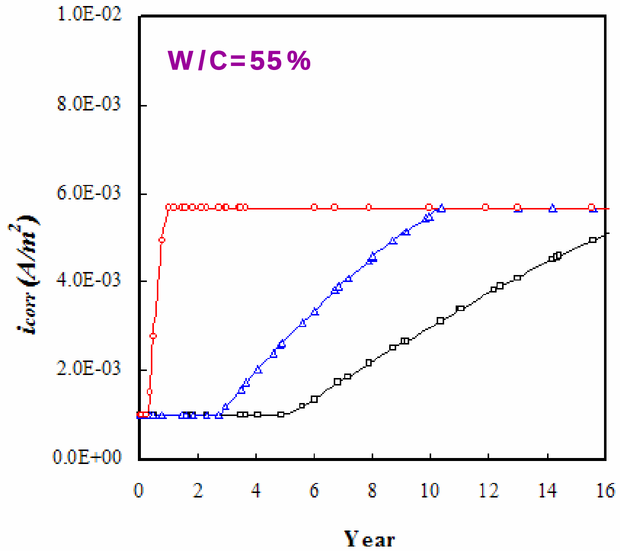
Analysis at Splash Zone (cover = 5cm)

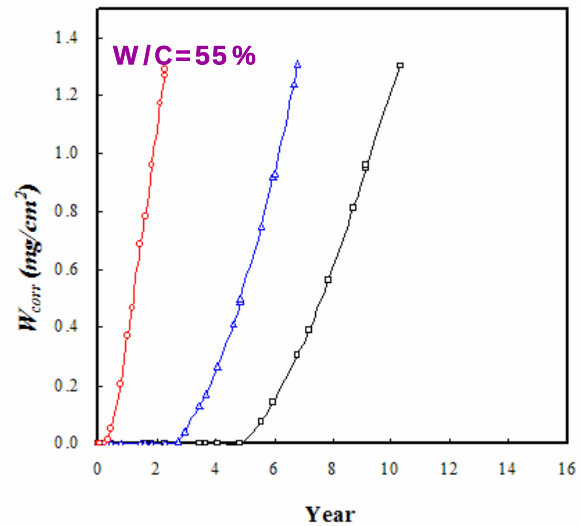






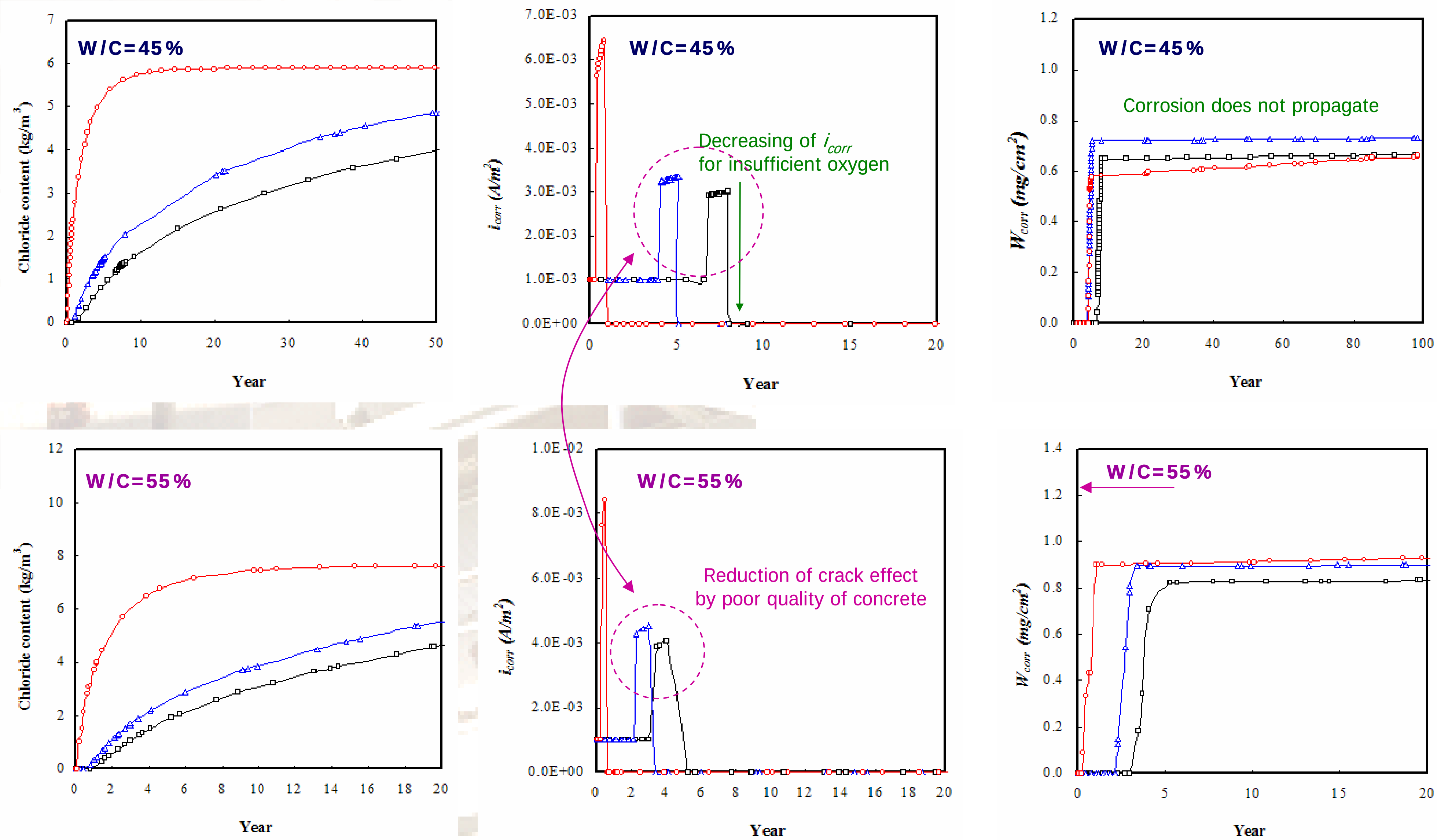






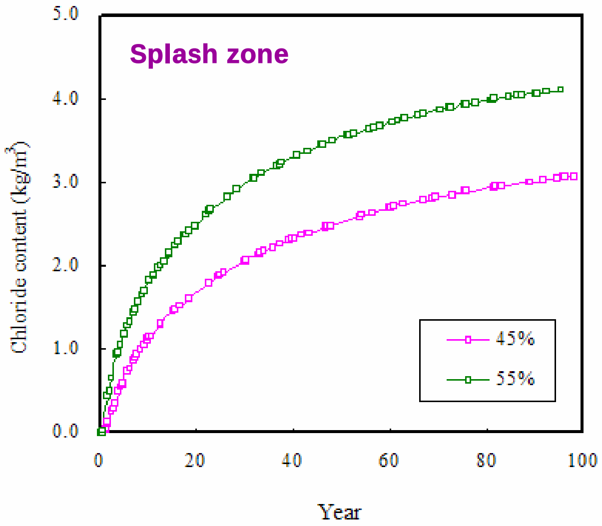
f_{ck} = 240 kgf/cm^2 , steel diameter : 32mm

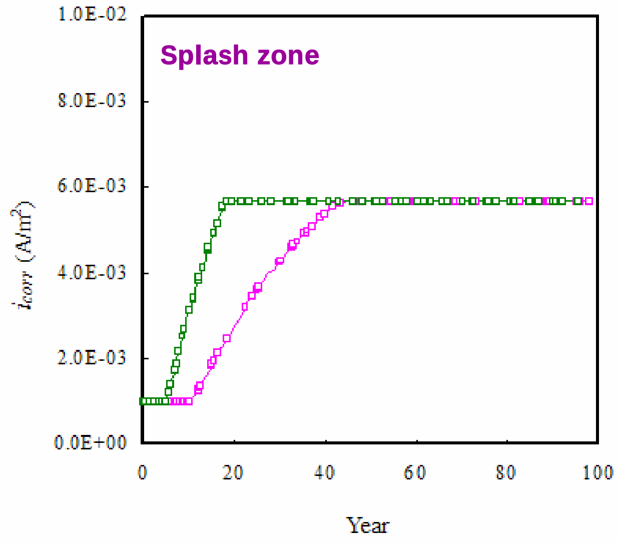
Analysis at Submerged Zone (cover = 5cm)

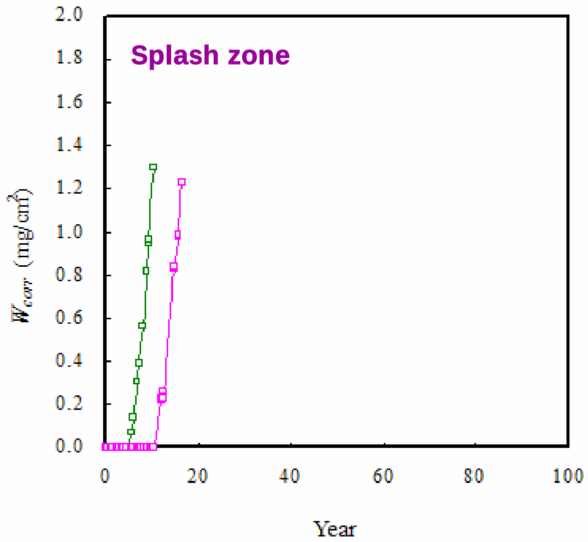


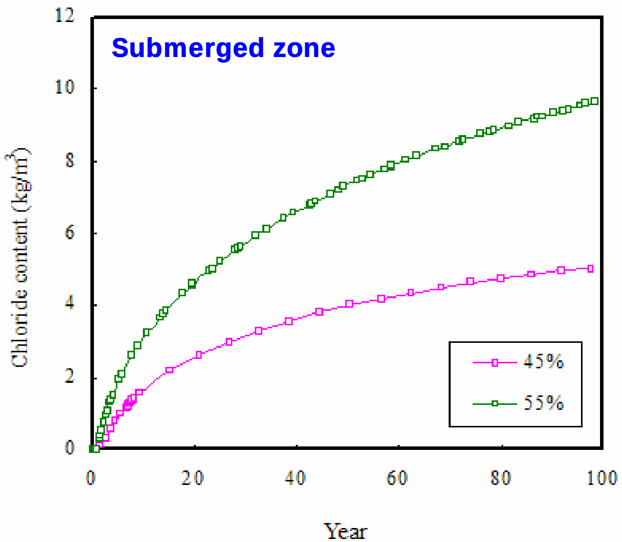
f_{ck} = 240 kgf/cm², steel diameter : 32mm

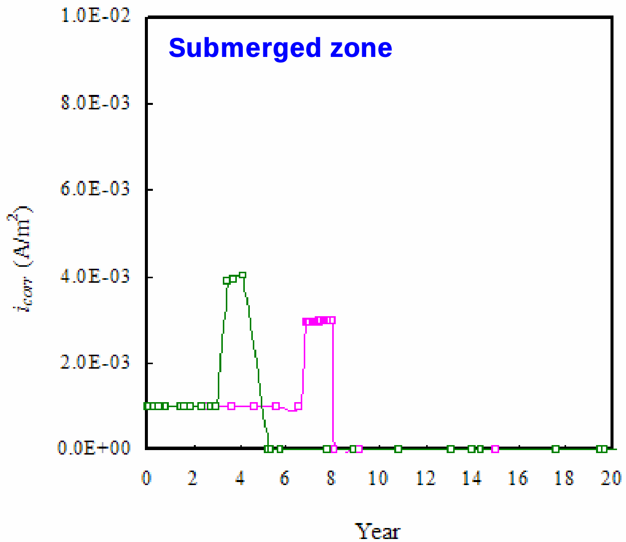
Quality of cover concrete (W/C =45% vs. W/C =55%)

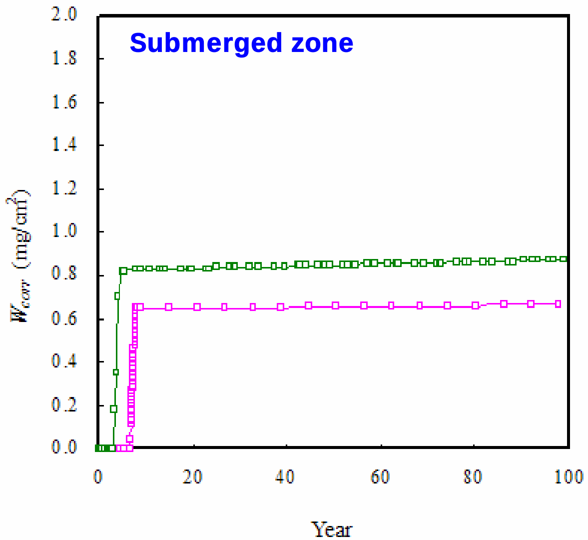






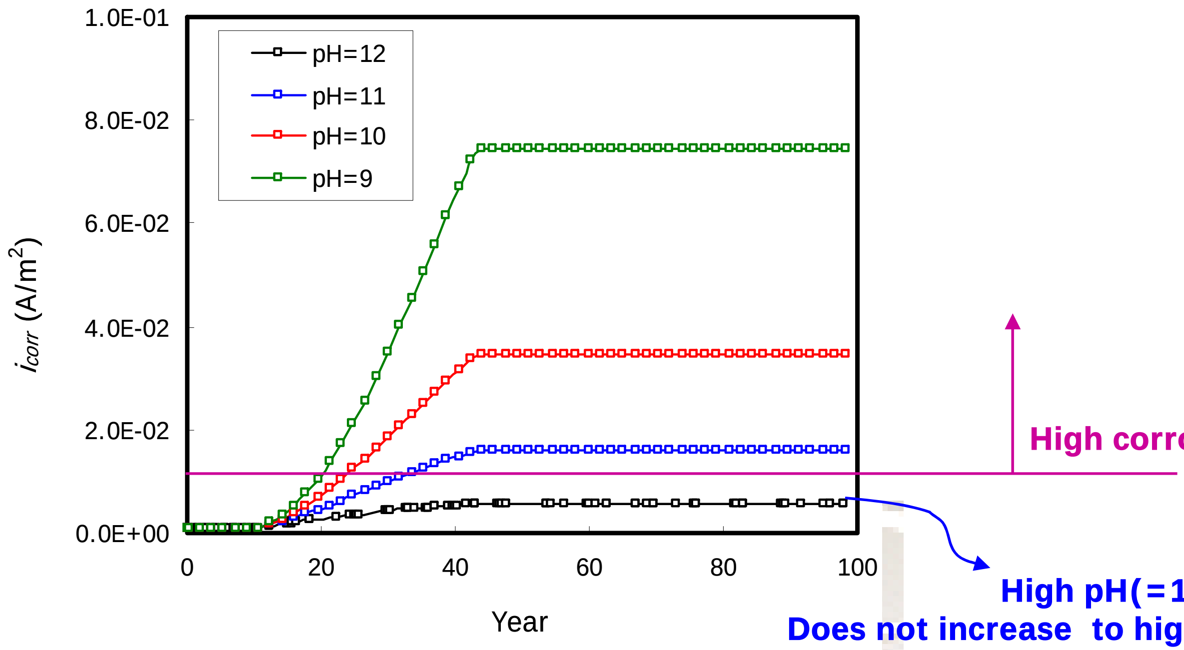






f_{ck} = 240 kgf/cm², steel diameter : 32mm

Corrosion rate with different pH

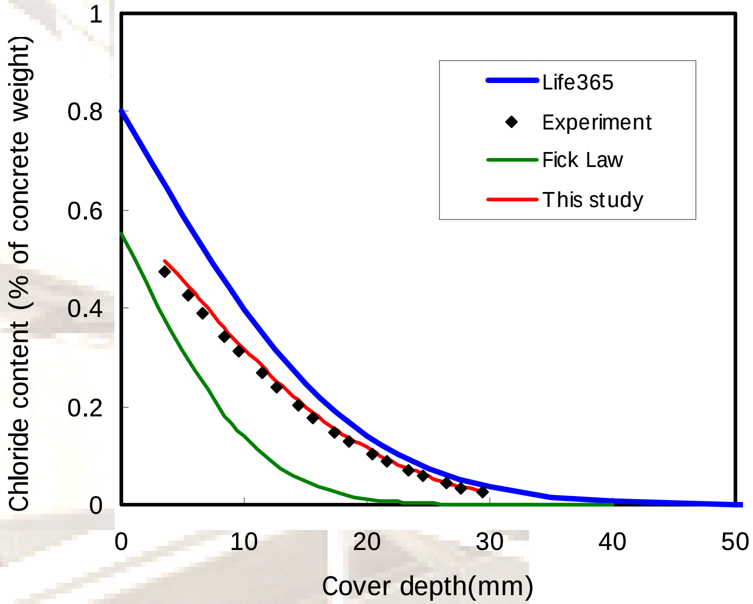


High pH(=12)
Does not increase to high corrosion rate

Criteria for Corrosion (Broomfield, 1997)

Condition	Corrosion Current Density
Passive Condition	$I_{corr} < 0.001\ A/m^2$
Low to Moderate Corrosion	$0.001 < I_{corr} < 0.005\ A/m^2$
Moderate to High Corrosion	$0.005 < I_{corr} < 0.01\ A/m^2$
High Corrosion	$I_{corr} > 0.01\ A/m^2$

Comparison of different prediction methods



		Fick's law	Life 365	This study
Penetration mechanism		Diffusion	Diffusion	Diffusion-penetration
D_{cl}	D28	Fixed D_{cl} $1X10^{-12}$ m^2/s	$D_{28} = 1\times10^{(-1206+2.40W/C)}$	$D_{28} = 1\times10^{(-1206+2.40W/C)}$
	Time effect		$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m$	$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m$
	Temperature effect		$D(T) = D_{ref}\exp\left[\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$	$D(T) = D_{ref}\exp\left[\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$
	Humidity effect			$D(h) = D_{ref}\left(1 + \frac{(1-h)^4}{(1-h_c)^4}\right)^{-1}$

Durability strategy using different mix proportion

Items / Mixing	W/C (%)	Unit weight (kg/m³)					B X (%)	
		W	Binder		S	G	Admixture	
			C	Slag			SP	AE
OPC 45%	45	164	365	-	735	1102	-	-
OPC 55%	55	160	291	-	812	1078	-	-
Change of mix proportion for design chloride diffusion coefficient using ***Slag with lower W/C***								
W/B 40% Slag 30%	**40**	**160**	**280**	**120**	**785**	**972**	**0.75**	**0.013**

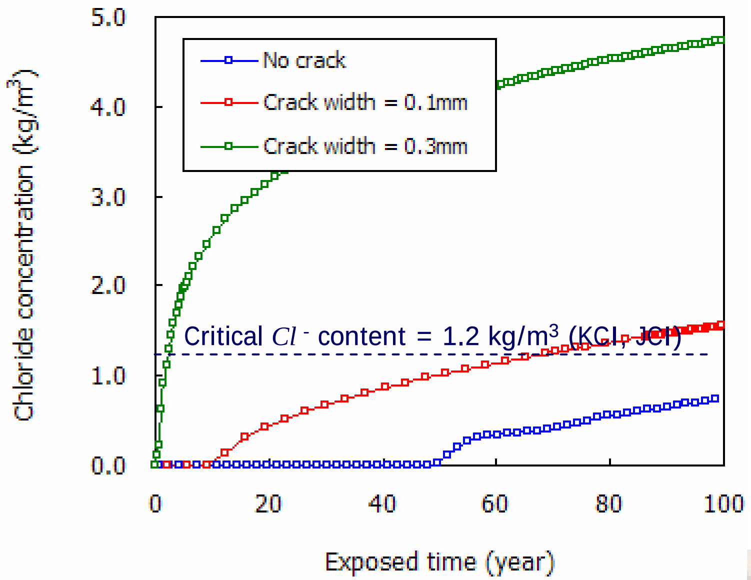
Envir.	Splash zone		Submerged zone	
W/C	45	55	45	55
$T_{w/o\ crack}$	**10.9**	**5.5**	**6.8**	**3.5**
$T_{w/\ crack}$	6.03	5.5	-	-

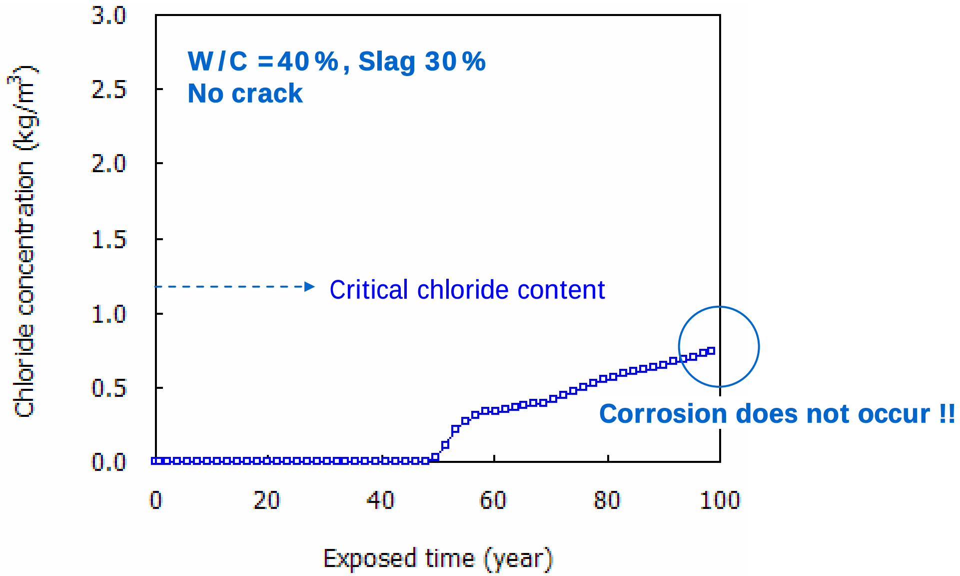
Increasing of cover depth
Increasing of pH in pore solution
Increasing of cover concrete quality

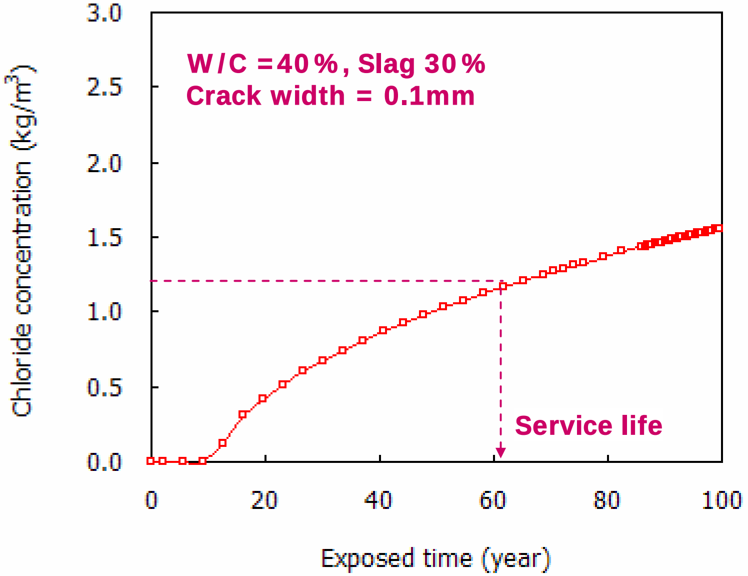
Decreasing of D_{cl}
Decreasing of W/C
Decreasing of external cl^- concentration

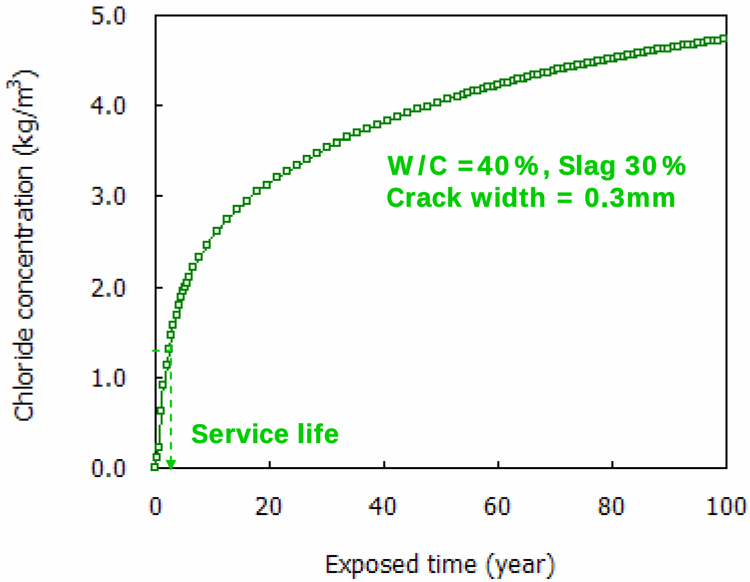
Increased service life of RC structures

Service life analysis for RC at splash zone (1)

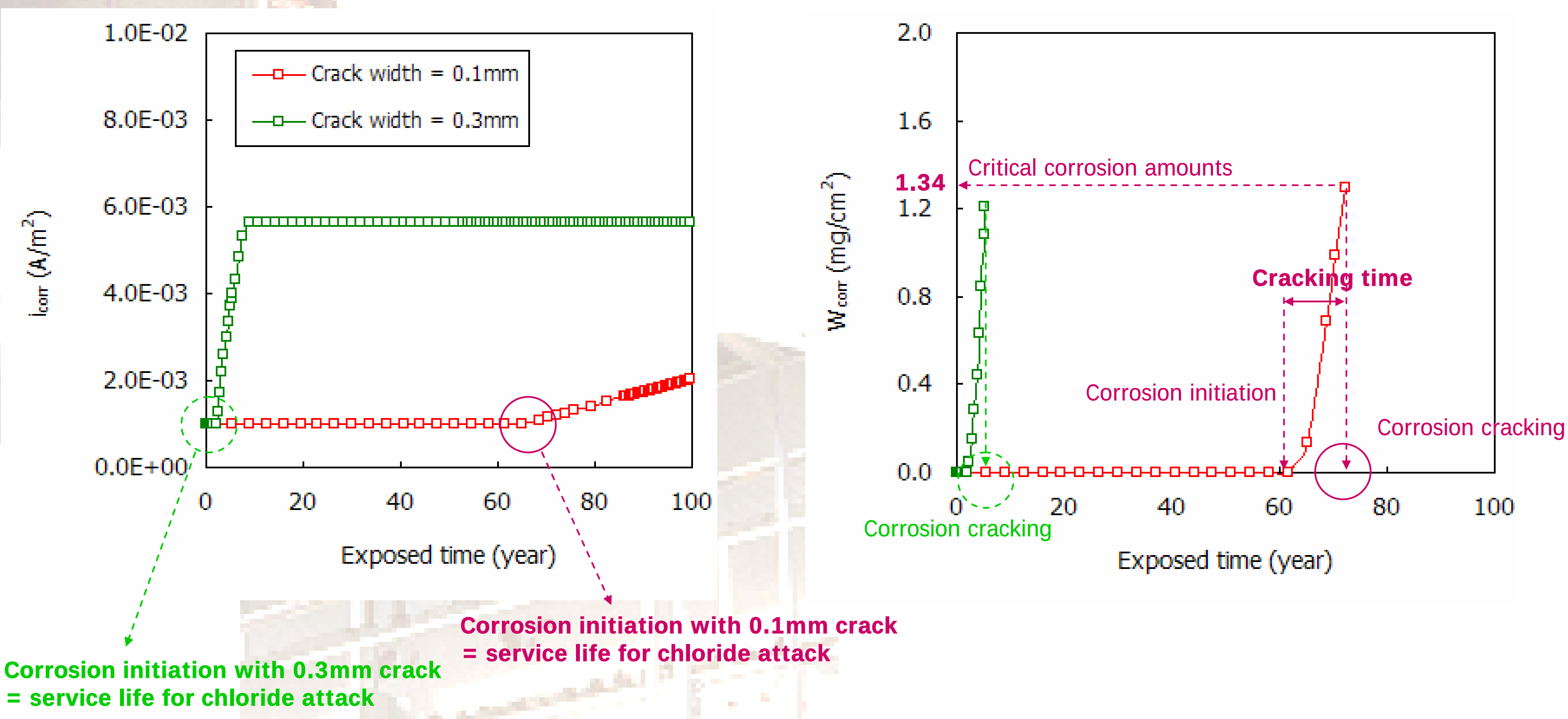




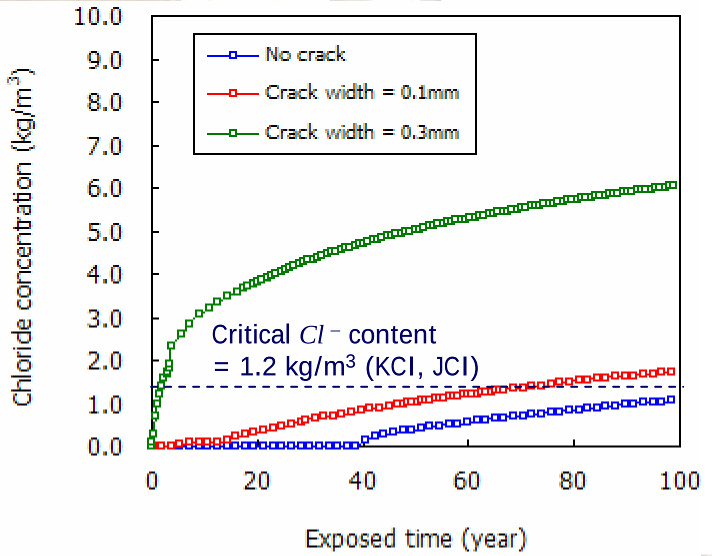


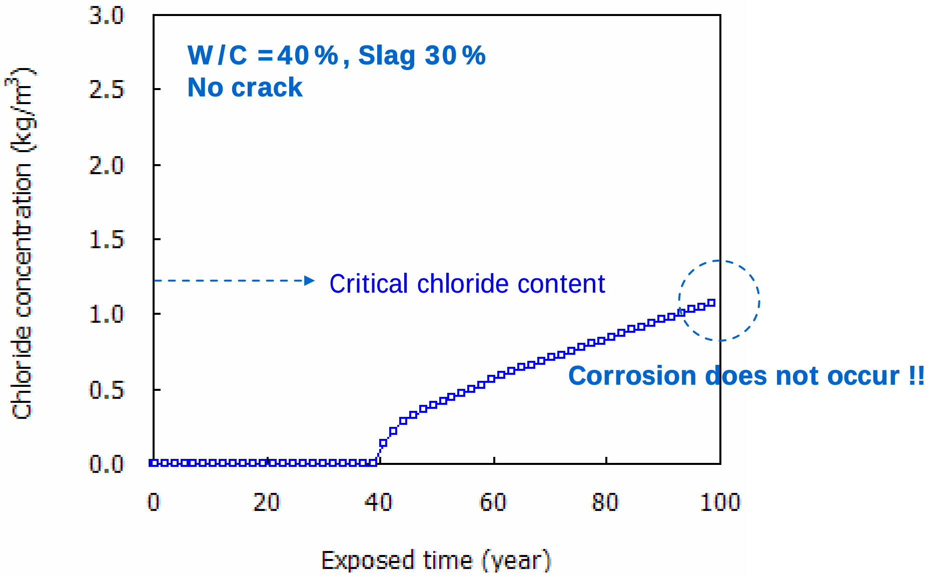


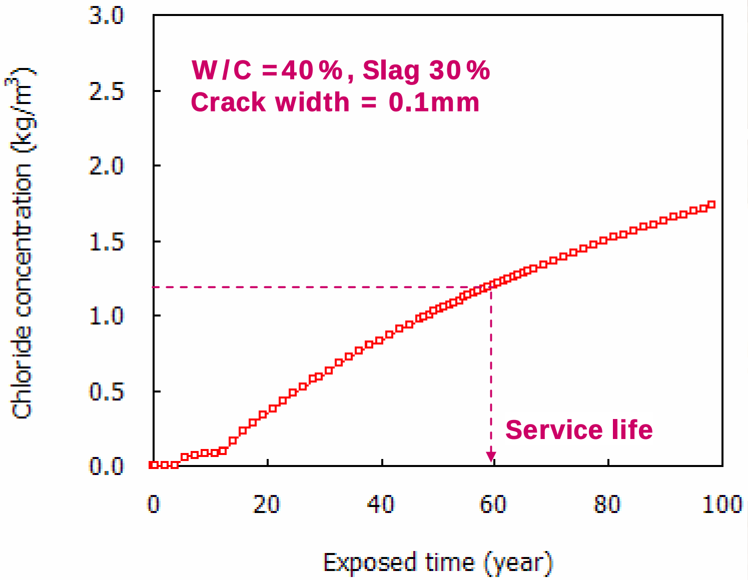
Service life analysis for RC at splash zone (2)

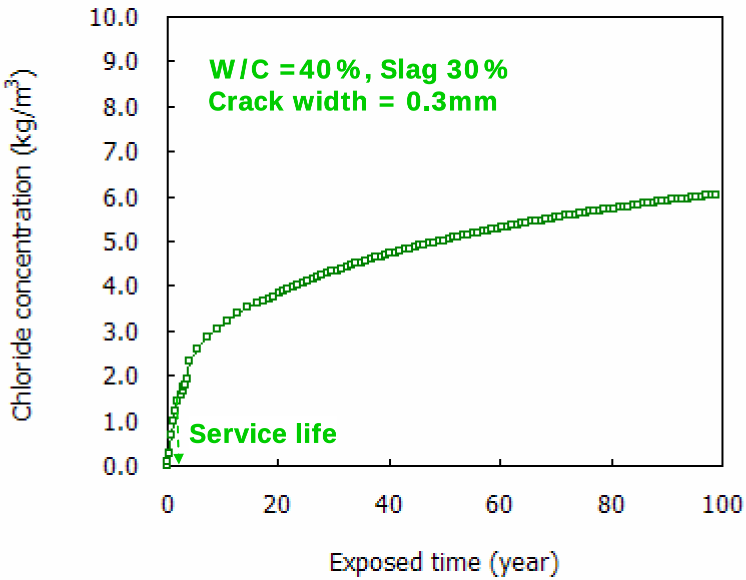


Service life analysis for RC at submerged zone (1)

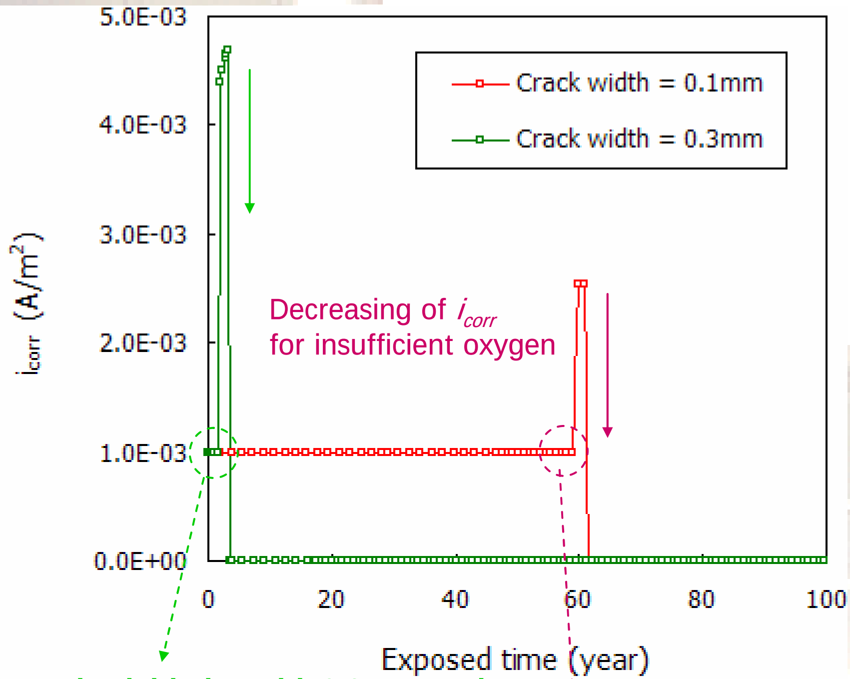


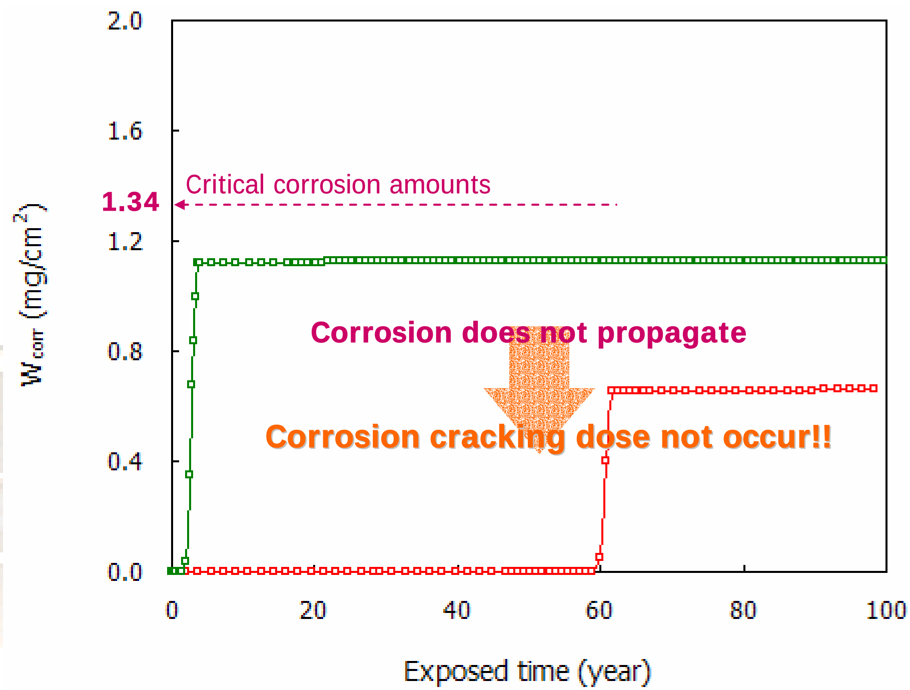






Service life analysis for RC at submerged zone (2)





Corrosion initiation with 0.3mm crack
=service life for chloride attack

Corrosion initiation with 0.1mm crack
=service life for chloride attack

Summary for service life

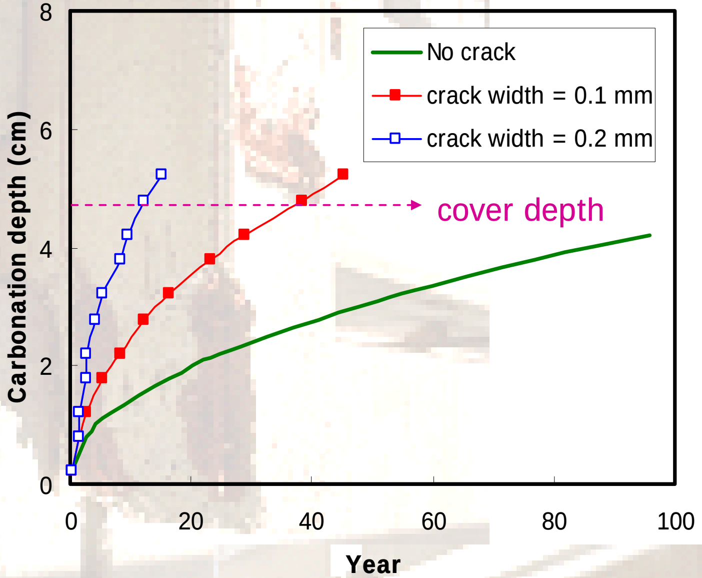
-	Splash zone		Submerged zone	
W/C	45	55	45	55
$T_{w/o\ crack}$	**10.9**	**5.5**	**6.8**	**3.5**
$T_{w/\ crack}$	6.03	5.5	-	-

W/B	W/B=40%, Slag=30%	W/B=40%, Slag=30%
$T_{w/o\ crack}$	**Over 100 yrs**	**Over 100 yrs**
$T_{w/\ crack}$	-	-

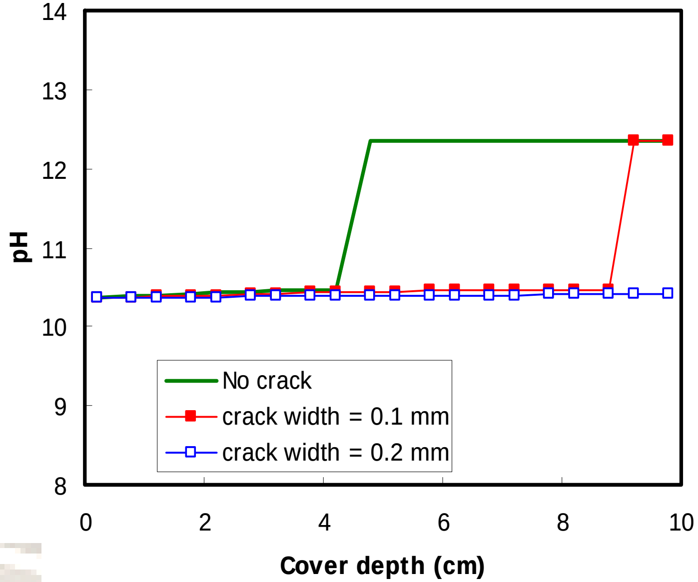
Need to control cracking in early age !!

-	Splash zone		Submerged zone	
Crack width	0.1mm	**0.3mm**	0.1mm	**0.3mm**
$T_{service}$	**65 yrs**	**2.5 yrs**	**59.8 yrs**	**1.5 yrs**

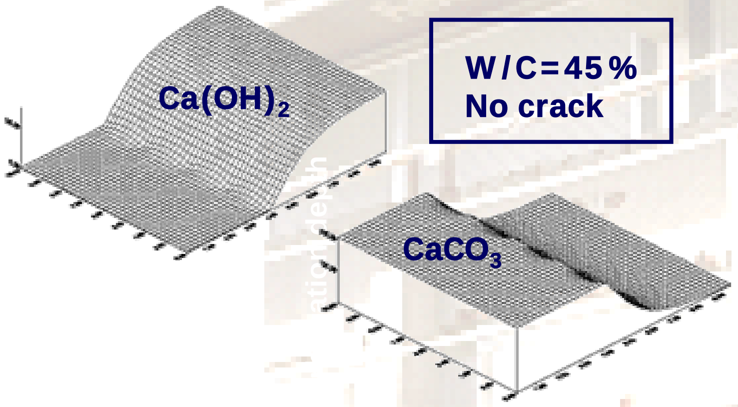
Carbonation analysis of liner concrete at tunnel



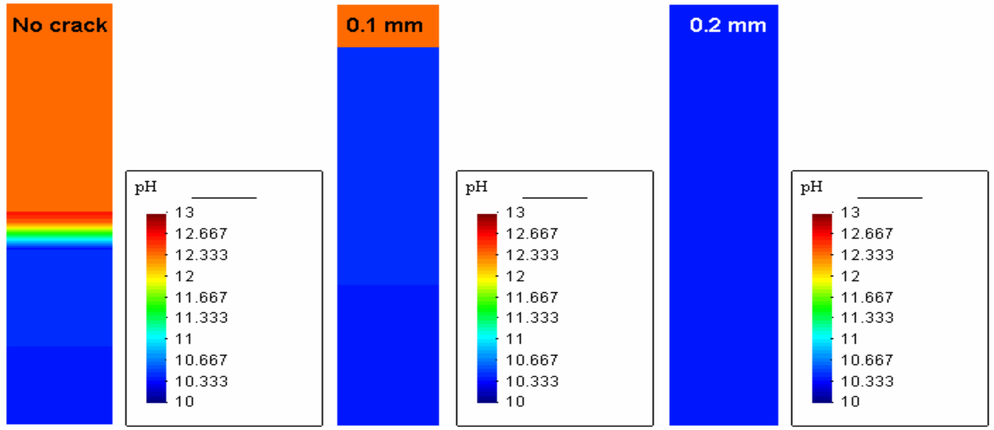
(a) Carbonation depth simulation



(b) Distribution of pH at 100 years



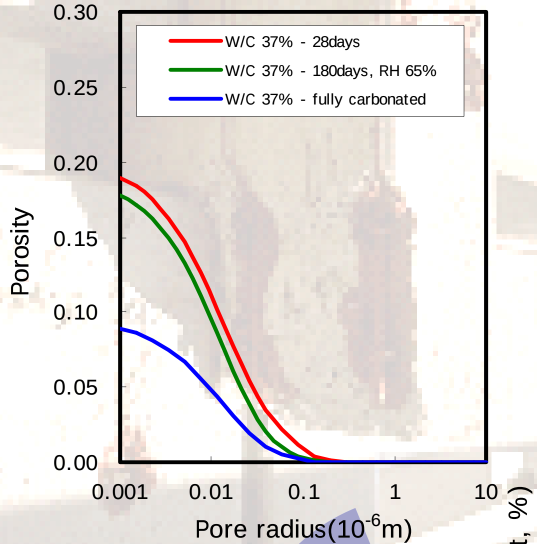
(c) Distribution of $Ca(OH)_2$ and $CaCO_3$



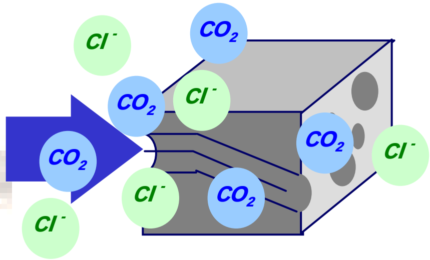
(d) Contour of carbonation depth at 100 years

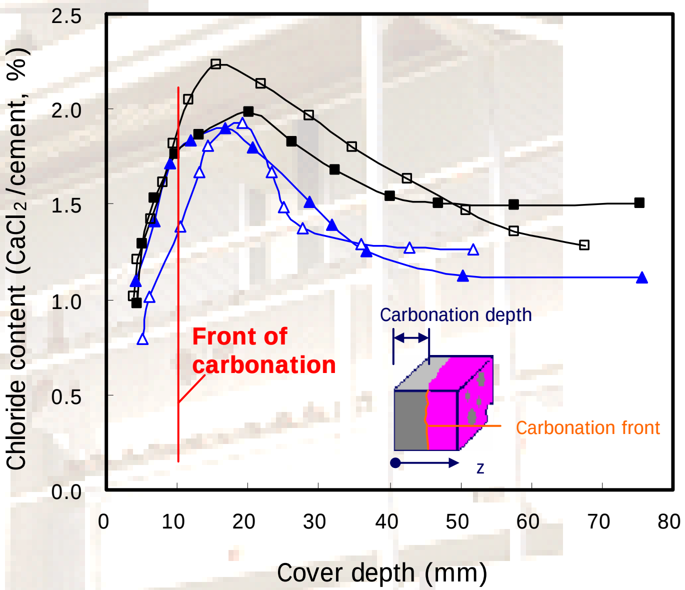
Chloride attack in carbonated concrete (1)

❖ ***Chloride distribution at carbonated area (Tuutti, 1982)***

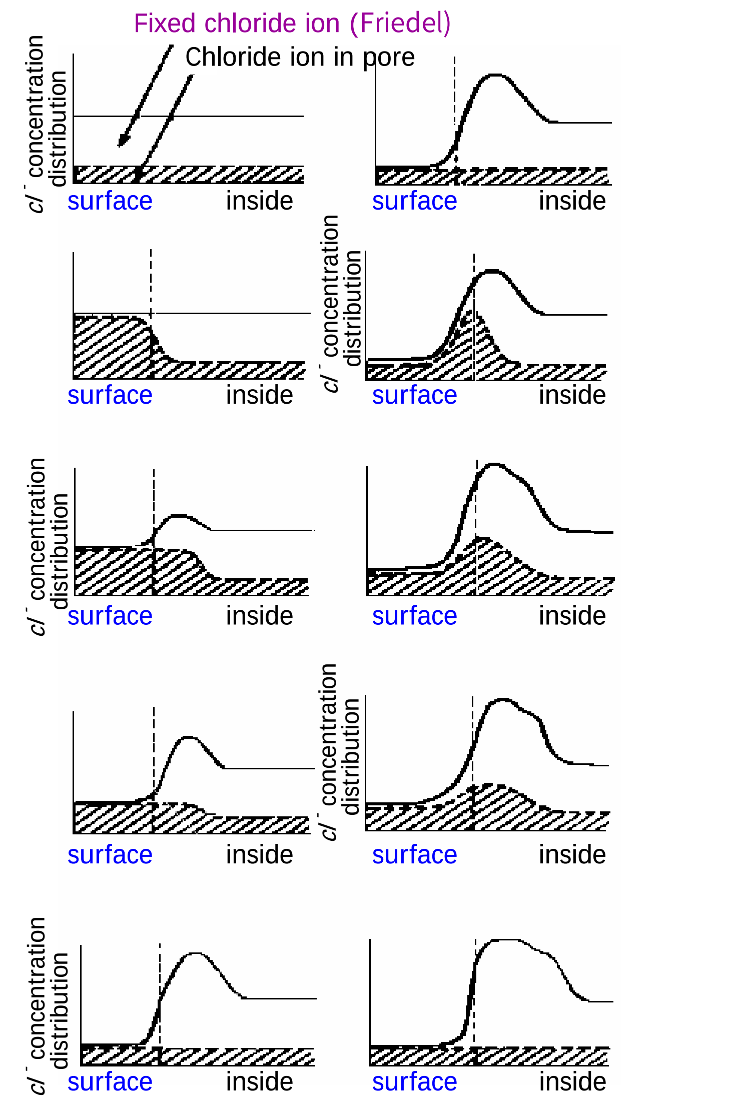


Decreasing of porosity



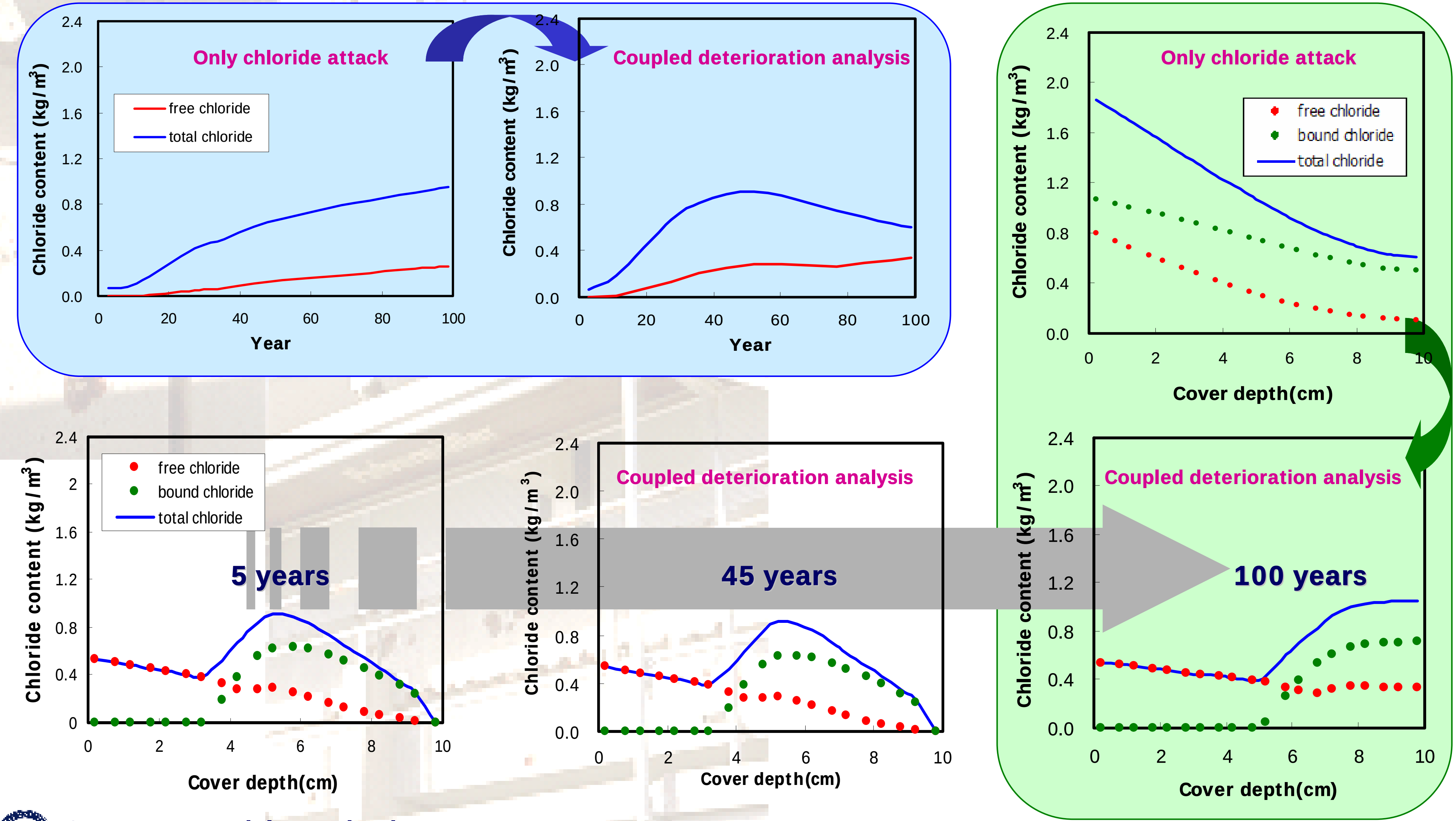


Carbonation initiation **Carbonation propagation**



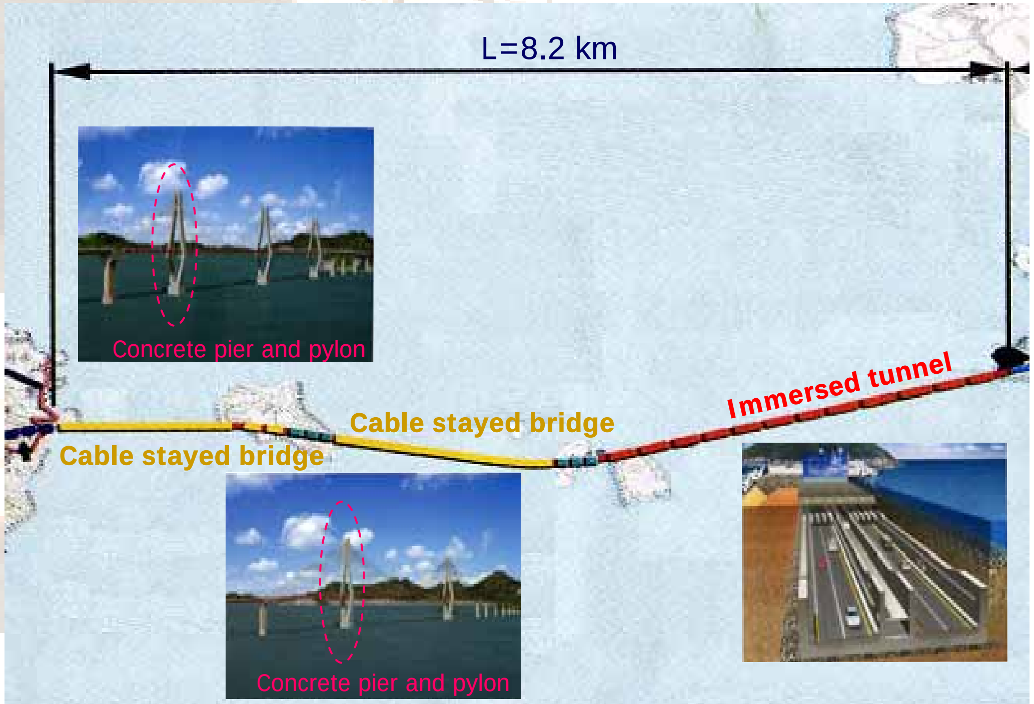
Concrete Materials, Mechanics & Engineering Lab., Yonsei Univ.

Chloride attack in carbonated concrete (2)



Concrete Materials, Mechanics & Engineering Lab., Yonsei Univ.

Service life prediction of RC structures
-an example of Busan-Geoje Fixed Link project in Korea



- **Design life:**
  100 years.
- **Nominal end of service life:**
  corrosion initiation
- **Level of Reliability:**
  90% (β = 1.3)

❖ *Environmental conditions*

Type of zones	Chloride concentration (mol/ℓ)	CO_2 concentration (ppm)	Temperature (°C)	Relative humidity (%)
Submerged	0.51	-	15.3	100
Splash	0.51	-	15.3	82.6
Atmospheric	0.19	-	15.3	65.3
Tunnel inside	-	670	20.0	65.3

❖ *Possible mix proportions*

Area	W/B		W (kg/m³)	Binder (kg/m³)				S (kg/m³)	G (kg/m³)	Admixture
				OPC	SLAG	SF	FA			
Bridge Structures	**B**1	0.350	140	160	160	-	80	751	1020	SP : 0.65~2.0% AE : 0.014~0.023%
	B2	0.375	142	184	184	11.4	-	797	1020	
	B3	0.375	142	152	152	-	76	765	1020	
	B4	0.375	143	143	143	-	72	782	1020	
Submerged Tunnel	**T**1	0.350	140	180	180	-	40	764	1020	
	T2	0.350	140	160	160	-	80	751	1020	
	T3	0.375	142	170	170	-	38	778	1020	
	T4	0.375	142	152	152	-	76	765	1020	

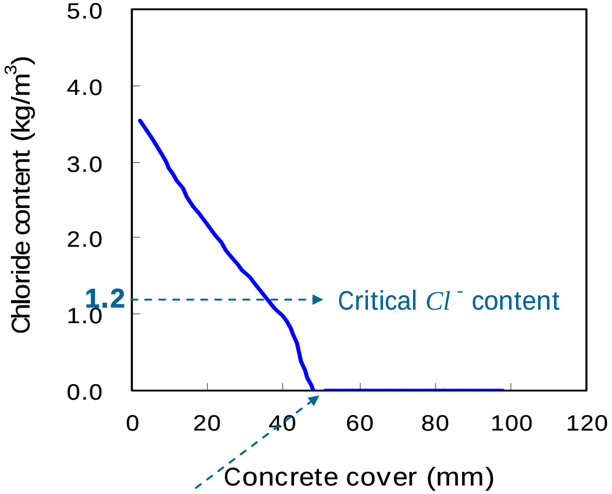
Specific gravity

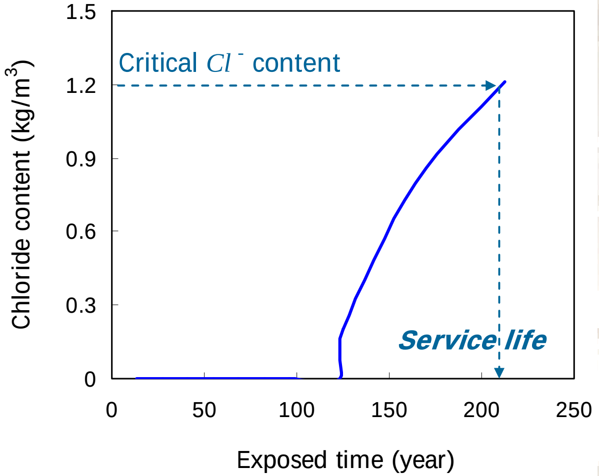
- Coarse aggregate : 2.64
- Cement : 3.16
- Fly ash : 2.19
- Sand : 2.58
- Slag : 2.89
- Silica fume : 2.21

Air content : 4.0%

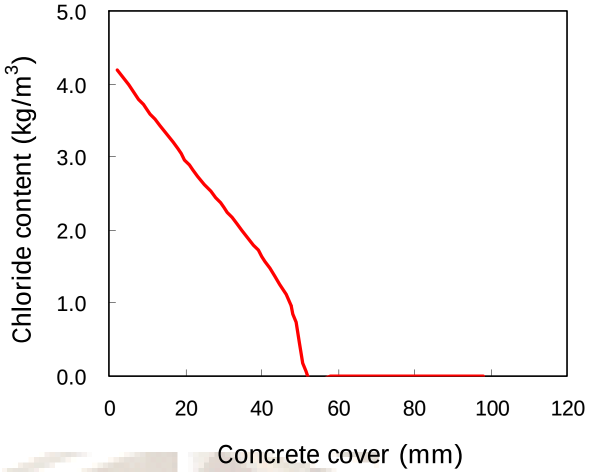
Analysis result at atmospheric zone(1)

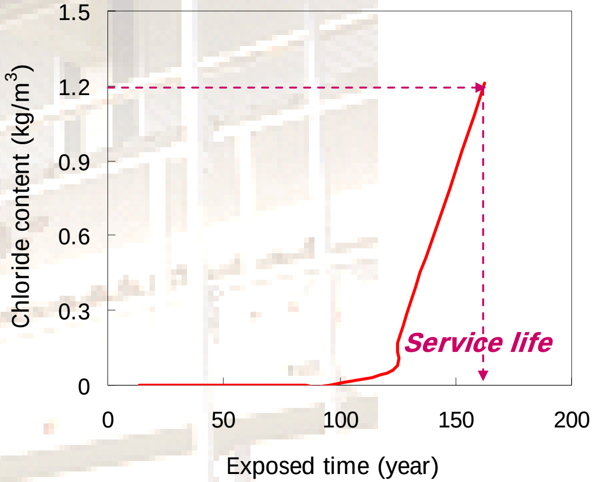
[Atmospheric – B1]



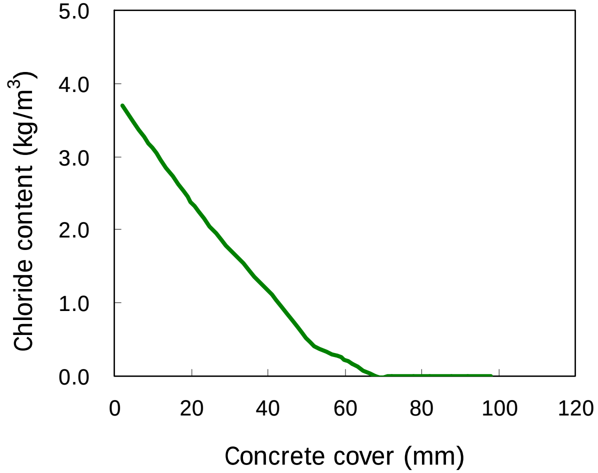


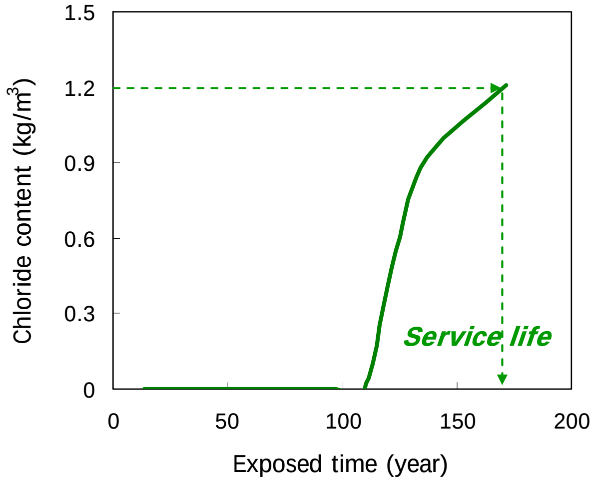
[Atmospheric – B2]





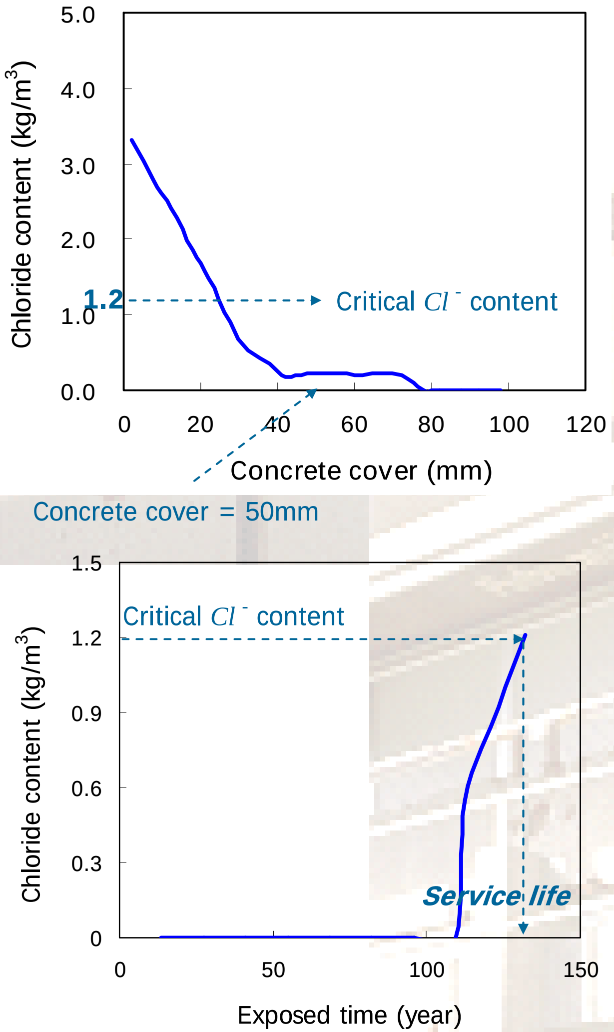
[Atmospheric – B3]



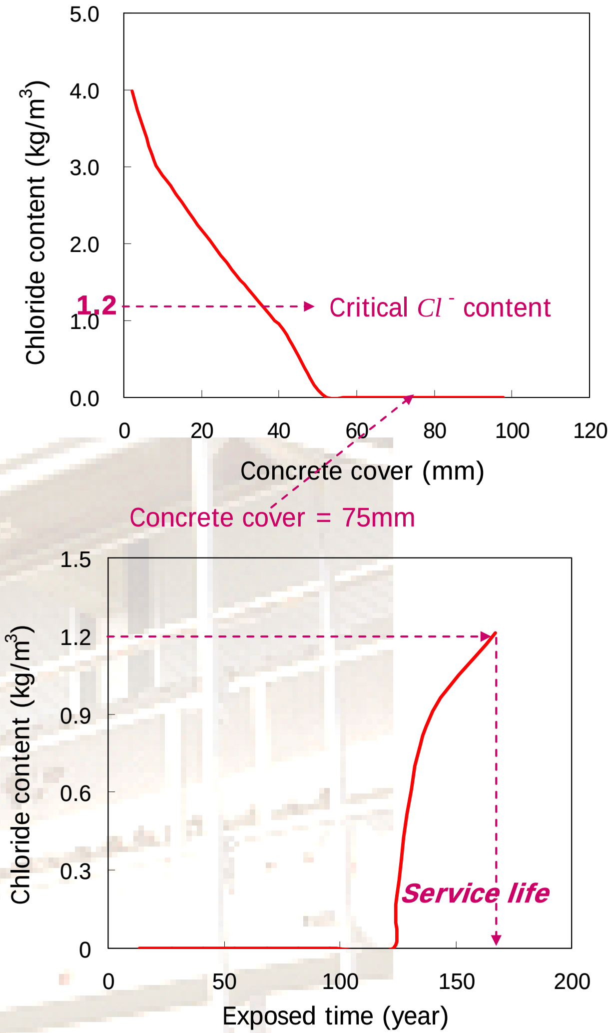


Analysis result at atmospheric (2)

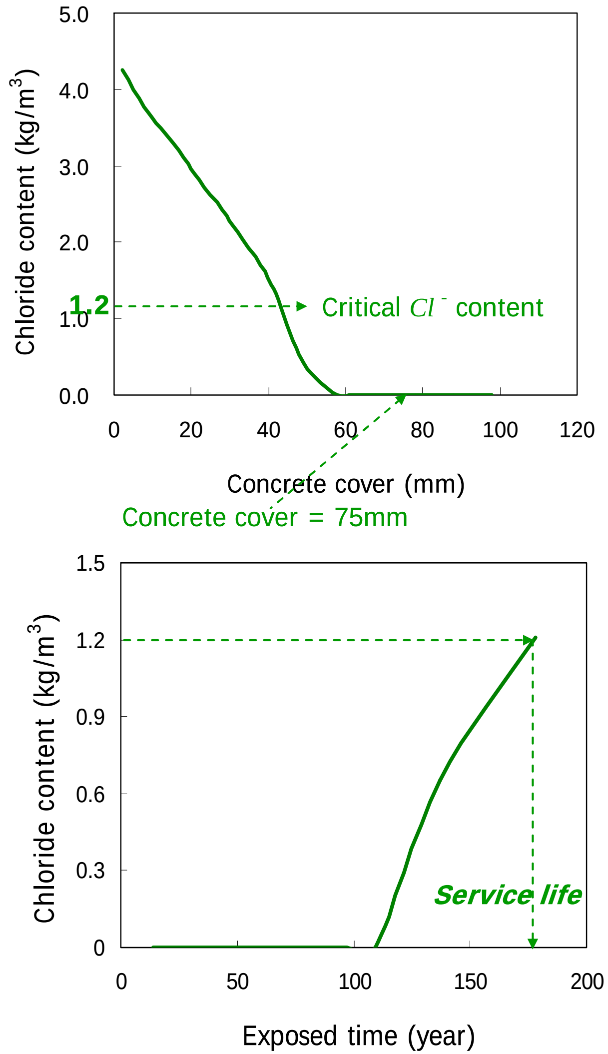
[Atmospheric – B4]



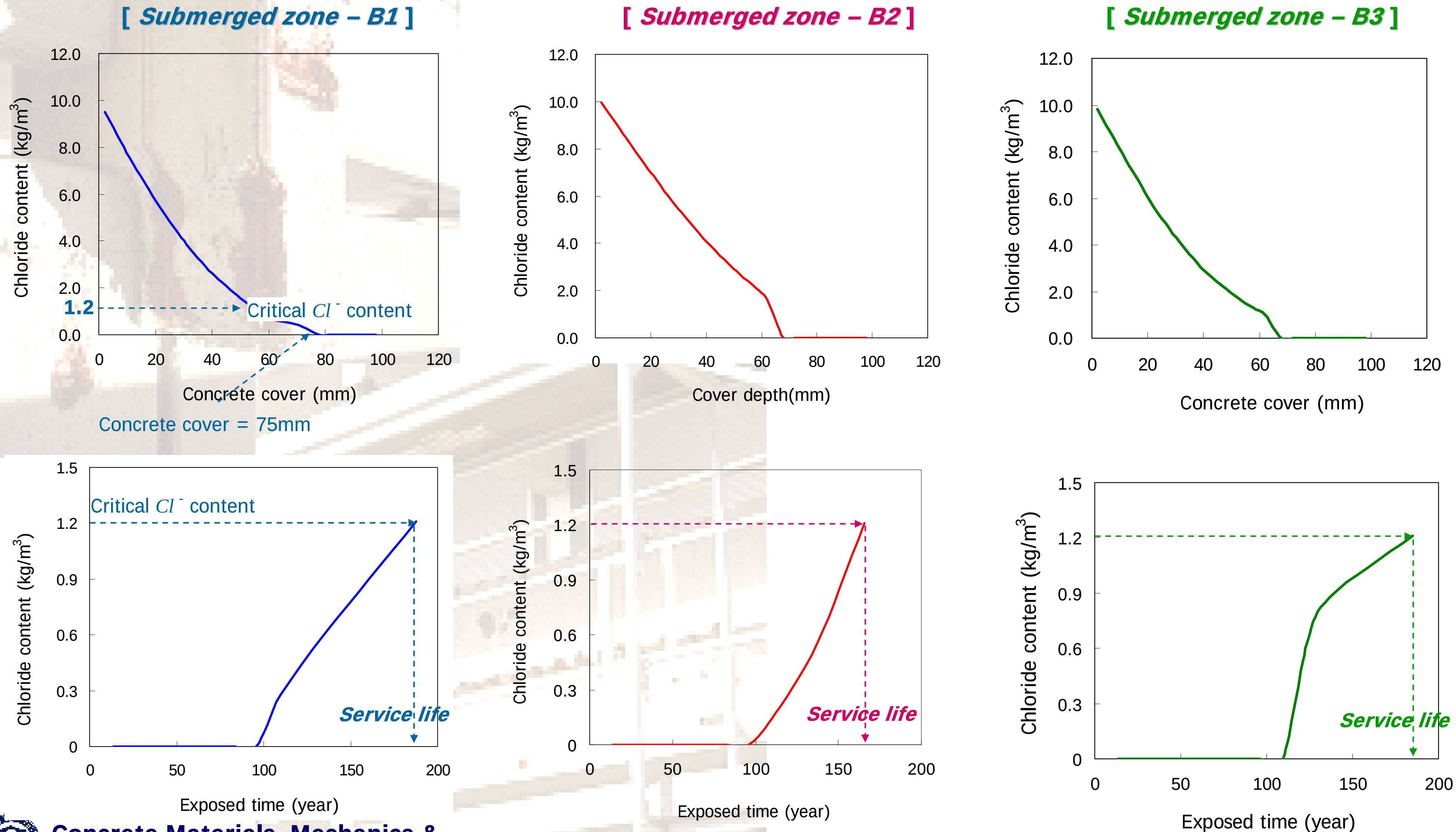
[Atmospheric – T1]



[Atmospheric – T3]

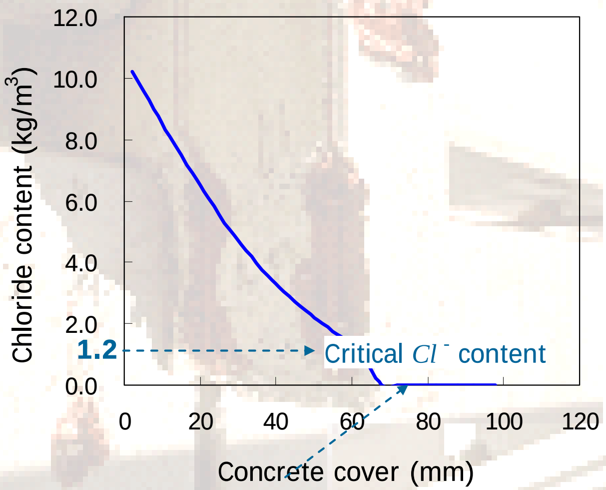


Analysis result at submerged zone (1)

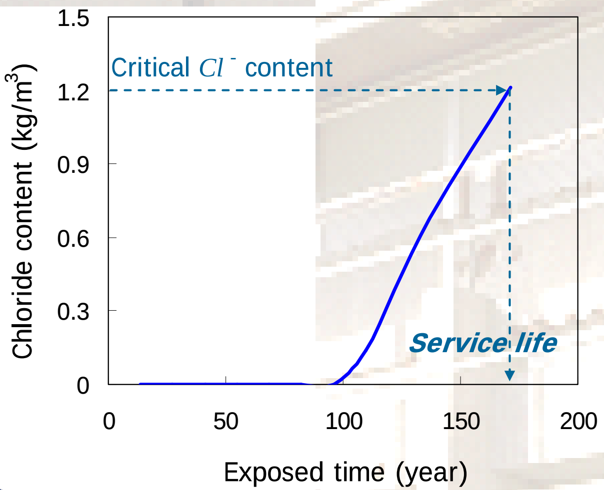


Analysis result at submerged zone (2)

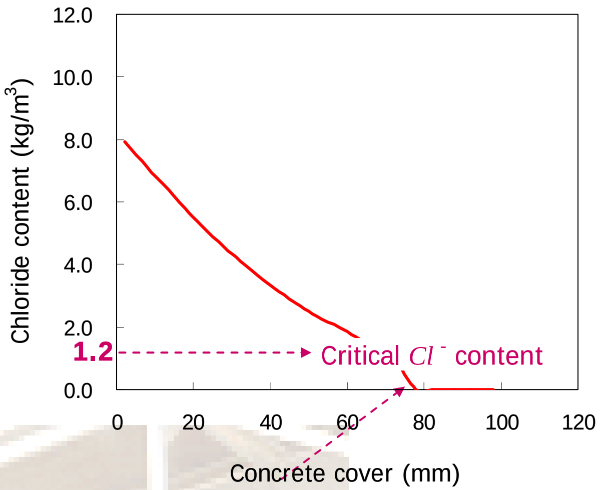
[Submerged zone – B4]



Concrete cover = 75mm

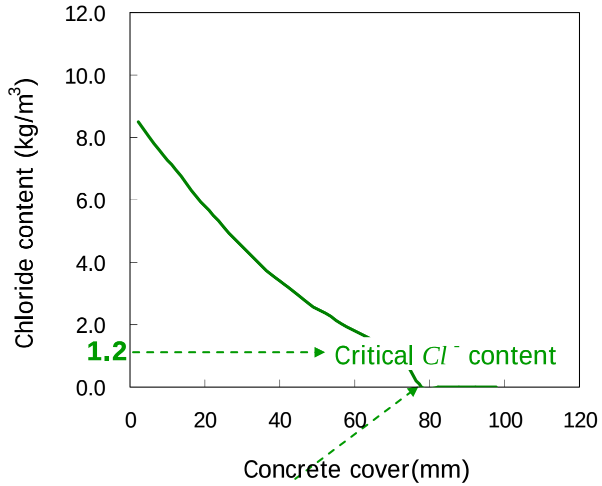


[Submerged zone – T1]

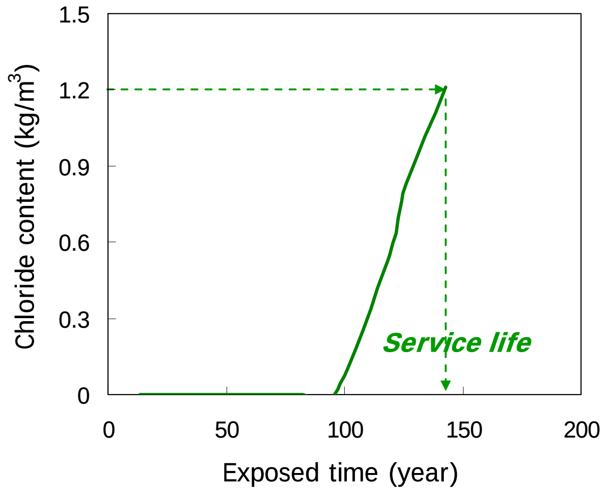


Concrete cover = 75mm

[Submerged zone – T3]

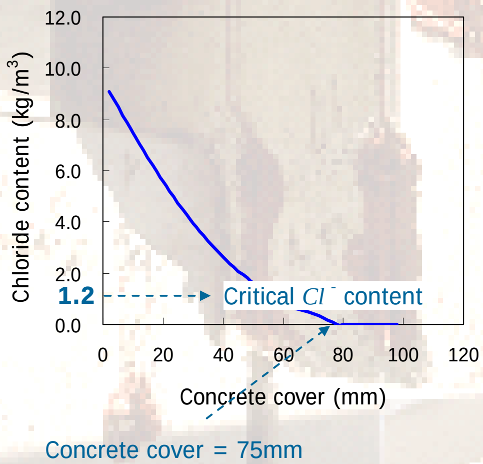


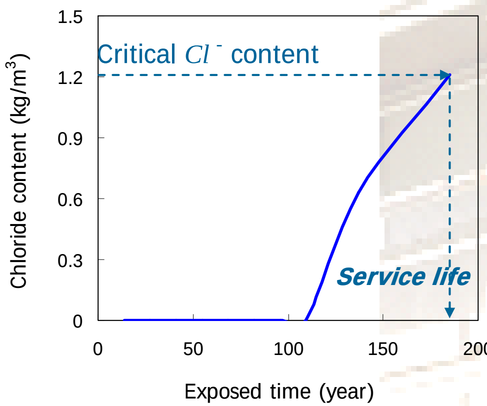
Concrete cover = 75mm



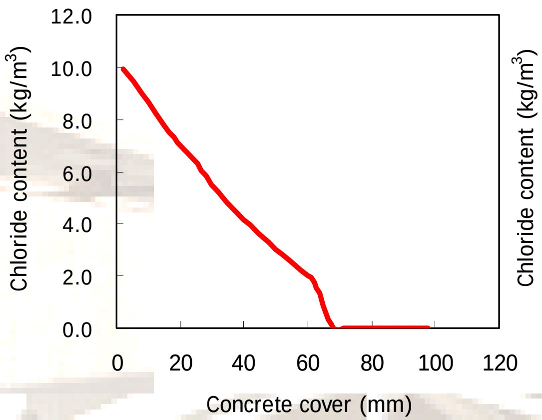
Analysis result at splash zone

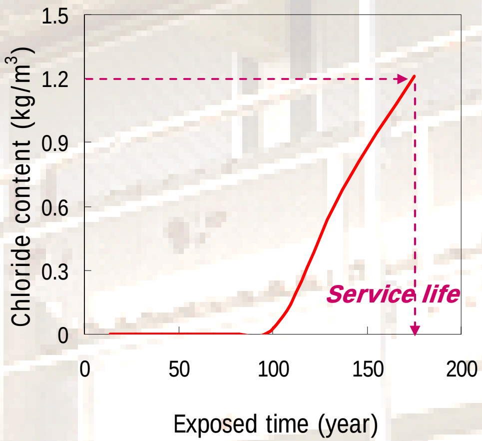
[Splash zone – B1]



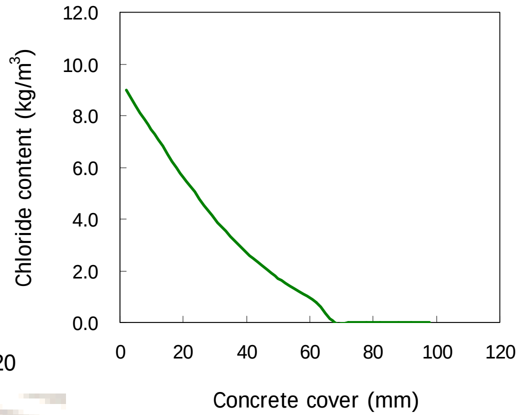


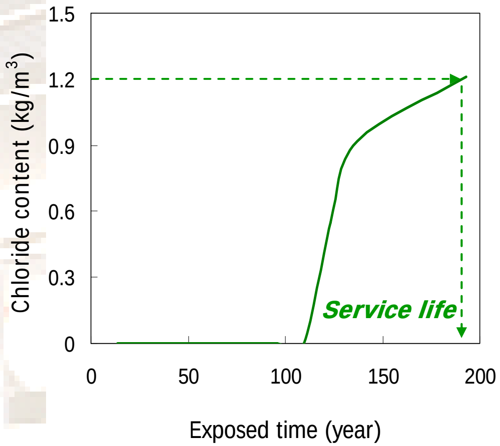
[Splash zone – B2]



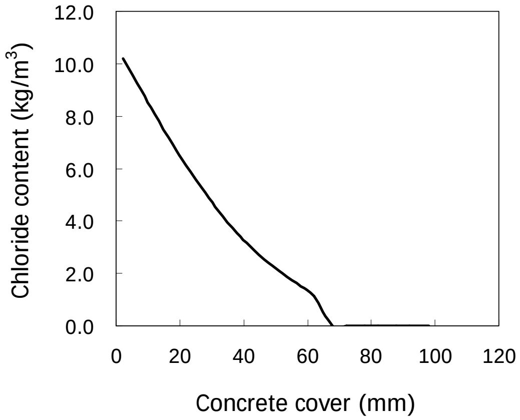


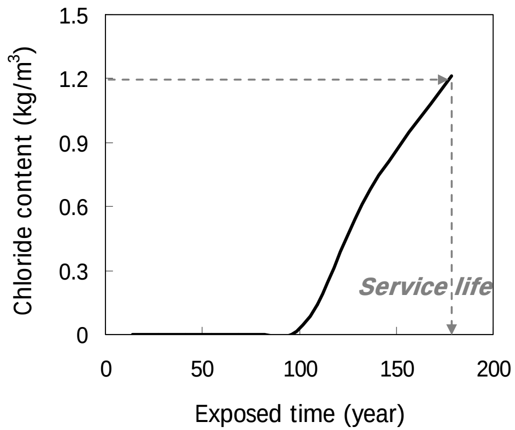
[Splash zone – B3]





[Splash zone – B4]





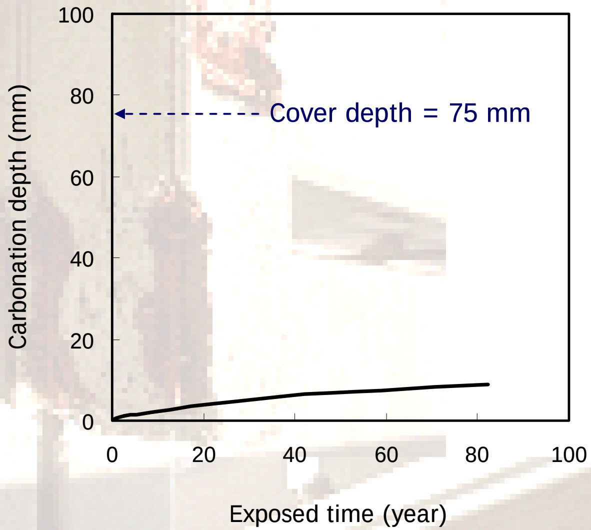
Summary of chloride attack analysis results

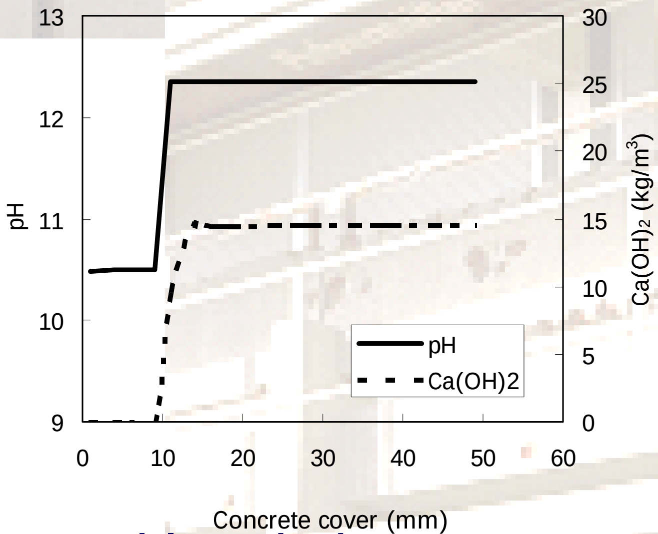
Area	Structures	Mix Type	Service Life (year)
Atmospheric Zone	Bridge (Piers & Pylons)	A-B-1	212
		A-B-2	162
		A-B-3	168
		A-B-4	132
	Immersed tunnel (inside)	A-T-1	167
		A-T-2	212
		A-T-3	178
		A-T-4	168
Submerged Zone	Caissons (external)	S-B-1	188
		S-B-2	165
		S-B-3	184
		S-B-4	171
	Immersed tunnel (outside)	S-T-1	152
		S-T-2	188
		S-T-3	143
		S-T-4	184
Tidal and Splash Zone	Pylons, Piers & Caissons	T-B-1	180
		T-B-2	175
		T-B-3	193
		T-B-4	176

→ **Satisfy the required service life for chloride attack**

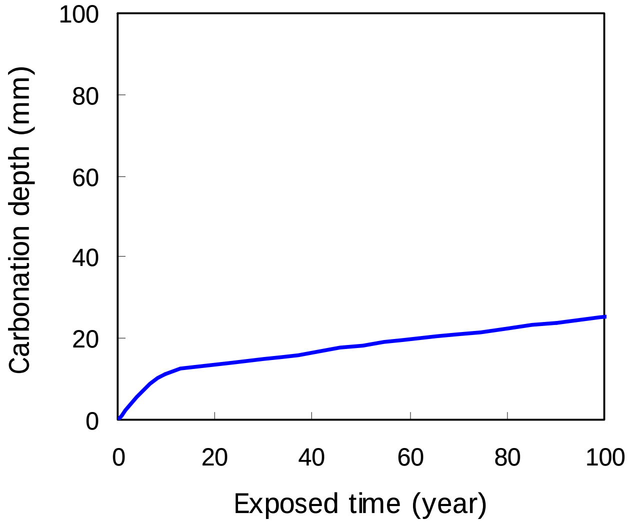
Analysis result for carbonation (1)

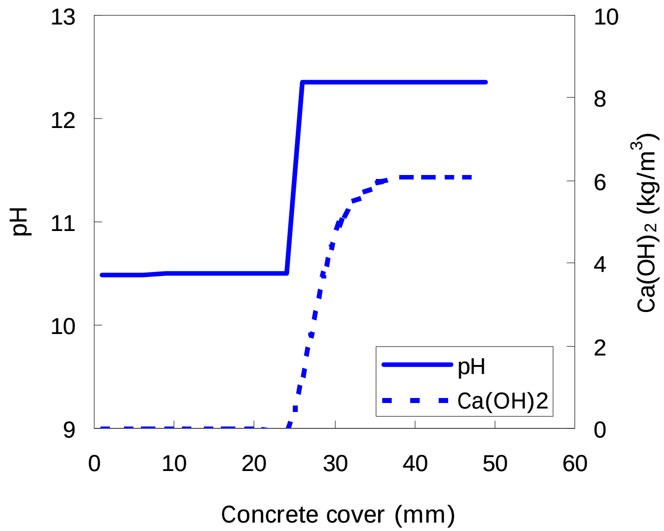
[Carbonation at tunnel inside – T1]





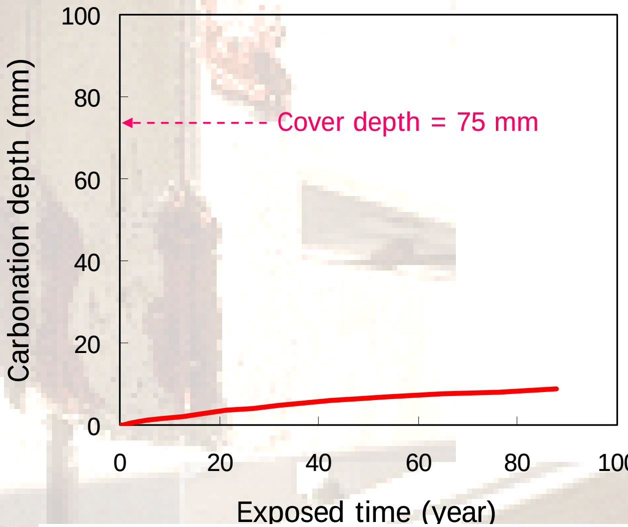
[Carbonation at tunnel inside – T2]

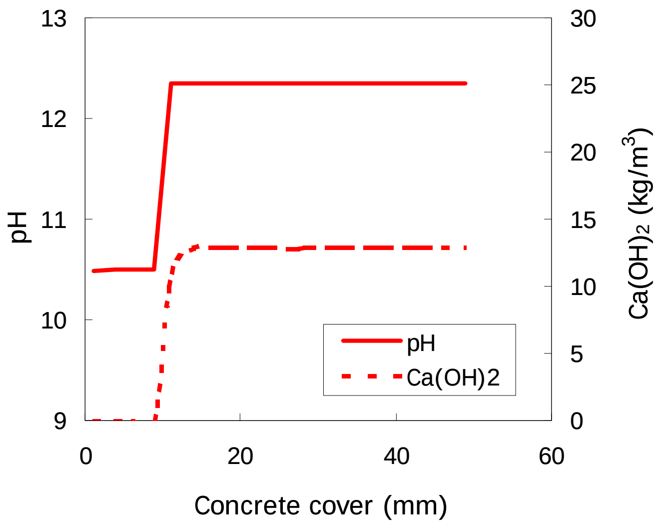




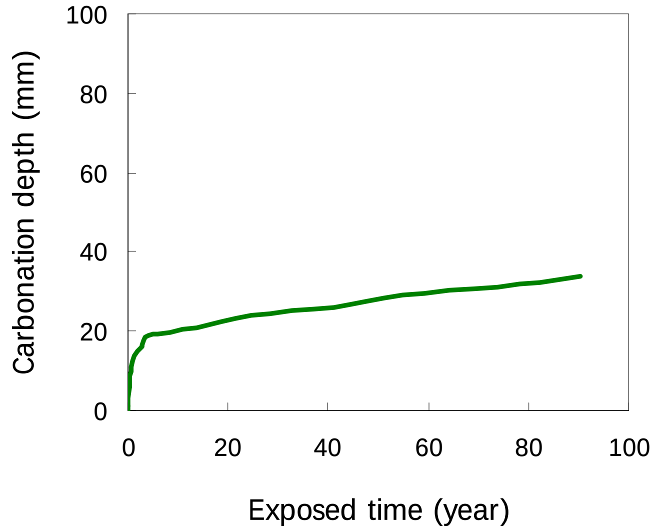
Analysis result for carbonation (2)

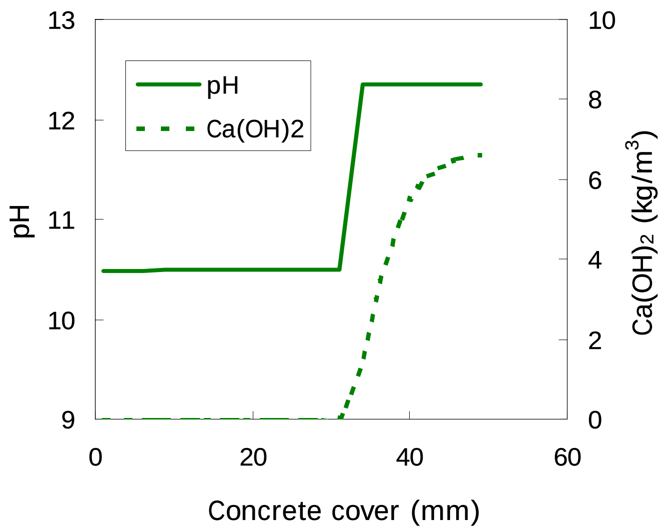
[Carbonation at tunnel inside – T3]





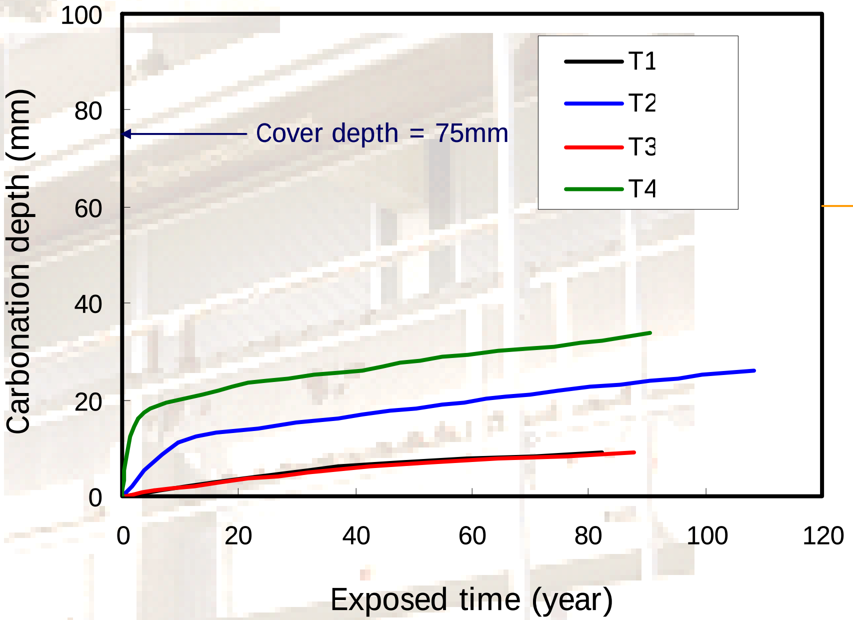
[Carbonation at tunnel inside – T4]





Summary of carbonation analysis results

Mix	Carbonation depth after 100 yrs (mm)	Service life for carbonation (yr)
T1	9.2	Over 300
T2	25	Over 250
T3	10	Over 300
T4	33	Over 250



Satisfy the required service life for carbonation

Conclusion

- Concepts for durability design and strategy along with performance based service life prediction in current RC design codes are presented.

- A scheme of coupled deterioration analysis using chloride penetration model and a carbonation model which consider the early-age behaviour and time-space dependent diffusivity of concrete as well as cracks inside concrete are proposed.

- In order to predict the service life of cracked concrete structures by both chloride attacks and carbonation, a microscopic steel corrosion model is also proposed and implemented into a finite element analysis program.
  - electric corrosion cell model : cl^-, *pH*
  - oxygen diffusion model : supplied O_2

- The service life of RC structures become shortens significantly with increased crack width, increased W/C, and decreased pH of pore water (i.e. carbonation).

- Optimum concrete mix proportions which make RC structures to possess the design service life can be obtained using this performance tool.

Thank you for your kind attention!

song@yonsei.ac.kr